Moss Landing Marine Laboratories

Technical Publication 73-4

A DRIFT CARD STUDY IN MONTEREY BAY, CALIFORNIA:

SPETEMBER 1971 TO APRIL 1973

Annual Report, Part 4, 1973

by

David D. Blaskovich

A NATIONAL SEA GRANT PROJECT
supported by the
OFFICE OF SEA GRANT PROGRAMS
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
DEPARTMENT OF COMMERCE
Grant No. SGP2-94

Robert E. Arnal, Sea Grant Project Coordinator

Moss Landing Marine Laboratories
of the
California State University and Colleges
Fresno, Hayward, Sacramento, San Francisco, San Jose, and Stanislaus

Contributions from the Moss Landing Marine Laboratories No. 44
Technical Publication 73-4
CACUC-MLML-TP-73-04

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ABSTRACT

Drift cards were released in Monterey Bay, California, to detect seasonal variations in the California Current system, and seasonal and diurnal wind variations in the immediate vicinity of the bay. About 23% of the cards were recovered, although the recovery rate varied from about 5% in the winter to about 60% in the late summer. Drift card speeds ranged from 1 to 8 km/day, in the winter and summer months respectively.

Good agreement was observed between geostrophic current, wind, drogue, and drift card data, although drift cards were observed to be primarily wind driven.

A weekend bias in drift card recoveries was observed for the entire period of study; however, it was less pronounced for those cards released during the summer months. Two bogus releases were used to estimate the discovery lag time, reported position accuracy, and longshore drift currents. Diurnal winds were observed during a 24-hour study, and indicated daily variations in the wind field may be as important as seasonal changes in moving surface water.

The drift card speed was observed to be about 3% of the wind velocity, and 1 m/sec was estimated as the minimum effective wind. The wind factor, ranging from 2.2% to 4.0%, was used to estimate the actual paths of drift cards and to examine the role of diurnal winds in affecting surface water movement.

ACKNOWLEDGMENTS

Hundreds of tourists and local residents, who can never be personally thanked, greatly contributed to the success of this project by returning drift cards they recovered along the western coast of the United States. Their promptness and accuracy in reporting information has resulted in a better understanding of Monterey Bay surface circulation and in reliable estimates of California Current velocities.

Stanley Phillips was essential in developing the original resources for the project. Sandra Benz, James Gendrom, and Scott McKain were of invaluable assistance in sealing, organizing, and releasing drift cards. I wish to thank Mr. R.C. Puckett of the Pacific Gas and Electric Company for providing the wind data from their files. This data has been shown to be both reliable and invaluable in understanding wind-driven surficial circulation in Monterey Bay.

This research was supervised by Dr. W.W. Broenkow of Moss Landing Marine Laboratories, and this report constitutes an M.A. thesis in the Department of Natural Science at San Jose State University. The author appreciates the help of his research committee: Dr. W.W. Broenkow, Chairman, Dr. J. Martin, and Dr. N. Felton.

I am also especially grateful to my wife, Lin, who served as a constant source of motivation throughout the development of this thesis, and who aided me in formulating the concepts of this work.

This research was supported by Grant No. SGP2-94 from the Office of Sea Grant Programs, National Oceanic and Atmospheric Administration, Department of Commerce, and by the Association of Monterey Bay Area Governments.

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CHAPTER 1

INTRODUCTION

In February 1971 an oceanographic study of Monterey Bay was begun by Moss Landing Marine Laboratories with the primary goal of identifying small-scale spatial variations in chemical and physical parameters that might reflect general features of the nearshore circulation. It became obvious that local governmental agencies were interested in our investigation, and the program was expanded in the summer of 1971, and further support was obtained in September that year (Smethie 1973). As a part of the expanded oceanographic program, we began a study of the movement of surface waters using drift cards with the intent of describing one component of the total circulation of bay waters.

Thus the immediate purpose of this study was to investigate the movement of surface water in Monterey Bay and to determine the relation between the surface drift current and the wind. The principal importance of this and similar drift card studies is to determine the fate of those substances which float on or in the surface film and are transported with the surface water.

This study is based on data collected monthly by this investigator and personnel of the Moss Landing Marine Laboratories between September 1971 and April 1973 concommittant with the hydrographic program (Smethie 1973). During a portion of this investigation (September 1971 to August 1972) our drift cards were released simultaneously by our colleagues at

Hopkins Marine Station during our mutual participation in the Association of Monterey Bay Area Governments (AMBAG) oceanographic study reported by Oceanographic Services, Inc. (OSI 1973). The Pacific Gas and Electric Company at Moss Landing, California, generously provided the wind data for the period of observation.

Region of Study

Monterey Bay is an area of relatively sparse population (300,000) and industry located on the Central California coast (Fig. 1 and 2). The bay is 42 km long and 16 km wide and its opening to the eastern Pacific Ocean is 37 km wide. The approximate area of the bay is 534 km^2, 19% of which lies over the Monterey Submarine Canyon, one of the world's largest (Martin 1964). The canyon is of high bathymetric relief, with depths ranging from 18 m within 0.3 km of the shore, to 865 m at the mouth of the bay.

Presently, the primary industry is a 2.1 million kilowatt fossil fuel power plant, located at the apex of the bay. This facility requires a shallow water anchorage for the docking and unloading of oil tankers. A second site is being considered which would accomodate larger tankers and would be located nearer to the submarine canyon in the central bay. Although the bay is not sheltered from the Pacific Ocean, the deep, navigable waters near shore make the bay readily available for development as a large tanker or shipping center.

The Monterey Bay area is well known for its scenic beauty and its

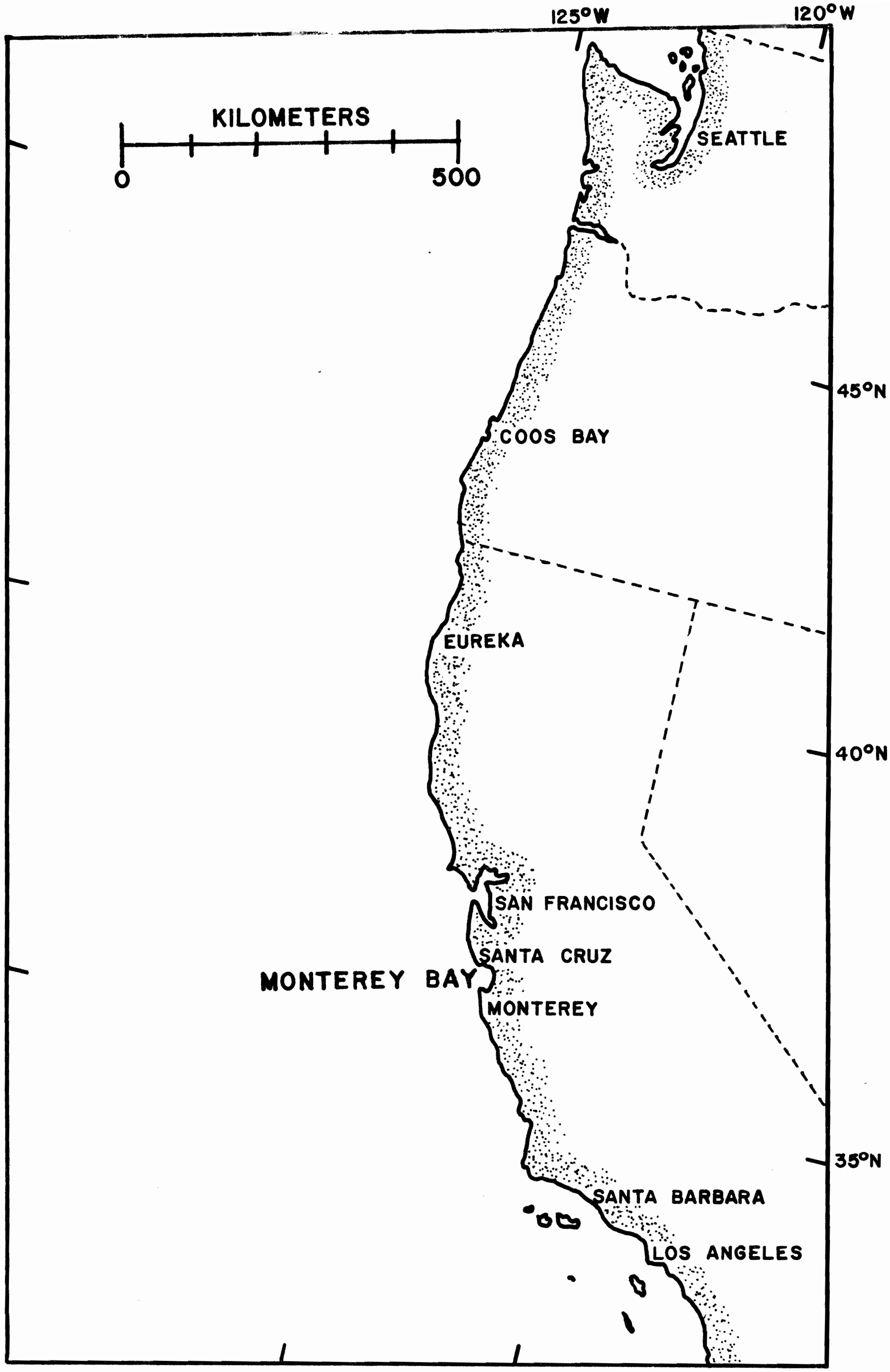

Figure 1. Chart of the west coast of the United States indicating the area of study.

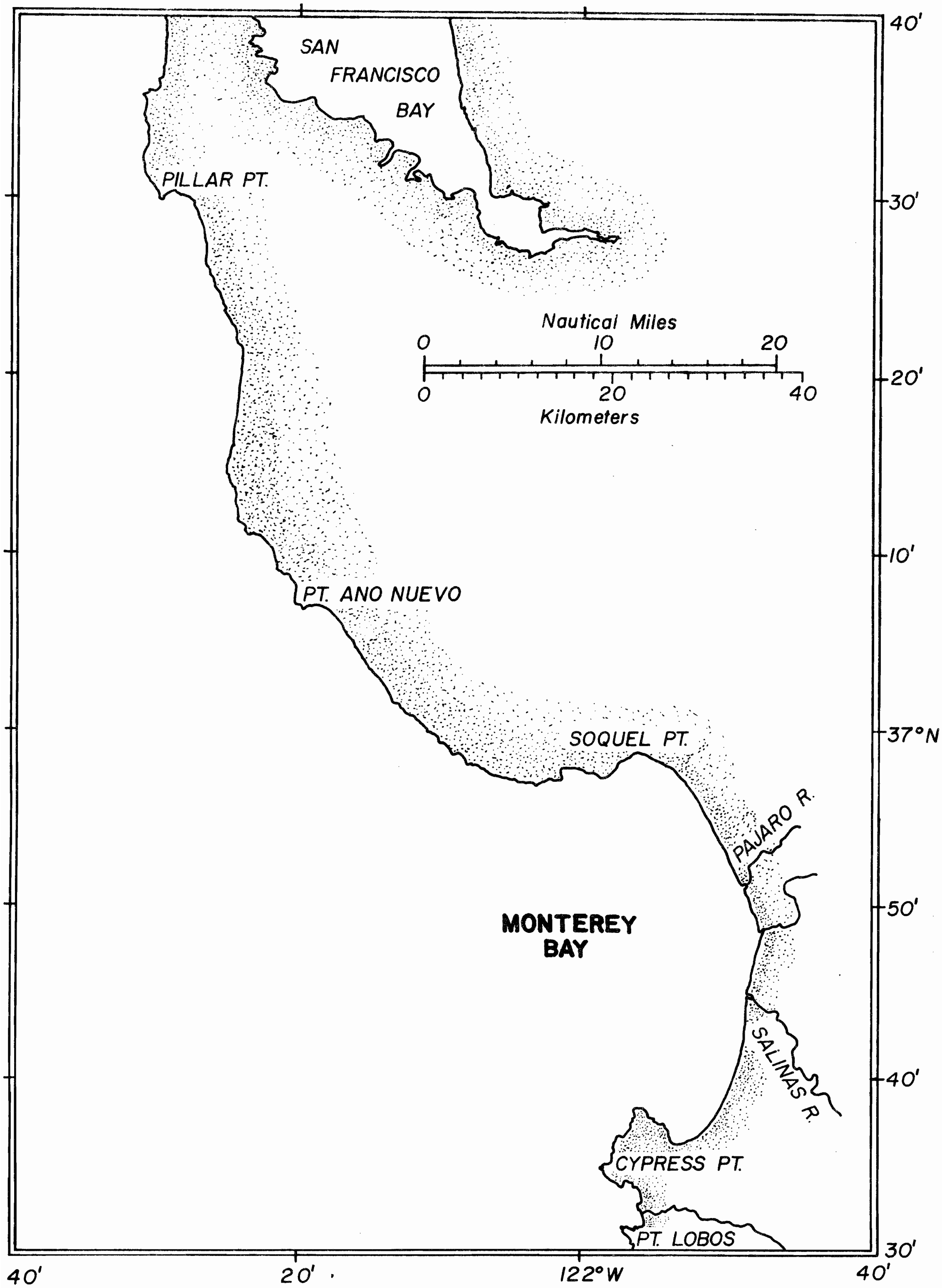

Figure 2. Region of study, Monterey Bay, California.

unique marine refuges, resulting in a high influx of tourists and an increasing population. To accomodate a larger population, domestic, municipal, and industrial facilities have expanded, producing an increased waste discharge into the bay. Oil spills, which have damaged Santa Barbara (Kolpack 1971) and San Francisco Bay (Conomos 1971, Smith 1973) have not yet occurred in Monterey Bay but must be anticipated. This requires a more detailed knowledge of the surface currents than now exists. Data from this study may be useful for predicting the movement of floating debris, sewage, and oil in the surface waters of Monterey Bay.

Previous Investigations

Several studies of the hydrography and the circulation patterns of Monterey Bay have been conducted, the first being those of Skogsberg (1936). Seasonal variations of temperature, salinity, nutrients, and plankton have been reported (Smethie 1972, Bolin and Abbott 1963); however, smaller-scale temporal and spatial variations have not been widely investigated. Other studies have described portions of the circulation in Monterey Bay (Breidenstein and Thomas 1965, Brennan and Meaux 1964, Broenkow and McKain 1972, Garcia 1971, Maratos 1971, Smith 1972, Stevenson 1964, McKay 1970, Griggs 1974); however, reports of the detailed movement of entire bay waters are lacking. In the following discussion, these and other drift card studies will be examined to develop an understanding of the circulation in Monterey Bay and the effective use of drift cards in documenting surface circulation patterns.

Tibby (1937) used drift bottles in conjunction with a hydrographic survey to establish the surface circulation between Point San Luis and San Diego. His analysis of drift bottle recoveries showed that surface circulation over a limited area can be effectively demonstrated by drift bottles alone. His data were used to account for the distribution of larvae and young fish that could not have been obtained from the dynamic computations alone. In the Caribbean Sea, Bruck's (1971) investigations of surface currents based on geostrophic calculations, thermocline topography, and drift bottle data were found to be complimentary, demonstrating further validity of the use of surface drifters. Dodimead and Hollister (1950) found drift bottle movement in the northeast Pacific Ocean to be in agreement with the geopotential topography, allowing for a component of wind-driven transisobaric movement to the right.

Wyatt, Burt, and Pattulo (1972) described detailed currents off the coast of Oregon with drift bottles. During the winter months, they observed the northerly flowing Davidson Current of 25 to 100 cm/sec within 20 miles of the coast. During the remainder of the year, a 15 cm/sec southerly flowing current was detected up to 4000 km from the coast, with the period of transition from northerly to southerly flow occurring in March or April.

Working within the immediate vicinity of Monterey Bay, Schwartzlose (1963) observed that the Davidson Current began as early as August and continued through May. Generally, this countercurrent was about 50 km wide, with drift bottles moving southerly beyond 50 km at sea. From April to August, the current outside the bay was generally southward, with some onshore and occasional northward movement occurring between San Francisco Bay and Monterey Bay during the summer. During the fall, winter, and early spring the countercurrent was a predominant feature of the coastal circulation from central California to British Columbia. When there was no countercurrent, the nearshore flow was southerly.

Although many brief circulation studies have been conducted, it is not clearly understood how the California Current and the seasonal wind field affect the circulation in Monterey Bay. Garcia (1971) postulated a cavitation flow model which would result in counterclockwise and clockwise flow in the northern and southern ends of the bay respectively. This dual gyre system would be driven by the California or Davidson Current and strongly modified by the Monterey Submarine Canyon. This hypothesis has been partially substantiated by 24-hour parachute drogue studies (OSI 1973, W. Broenkow, unpublished data) which suggest a bifurcation at the head of Monterey Submarine Canyon. However, this simple circulation pattern does not adequately explain the complex current trajectories which have been observed.

Results of the most comprehensive study (OSI 1973) indicate a generally northerly 15 to 25 cm/sec flow within Monterey Bay, and a clockwise eddy in south bay of 2 to 5 cm/sec. This conclusion was based upon the movement of drogues and dye patches and demonstrated that current speeds within the bay are slower than in the open ocean just offshore. Over the area of Monterey Submarine Canyon, an offshore flow of surface water was usually observed. Griggs (1974), using surface drifters, observed a seasonal flow pattern similar to the California Current system, with a northerly flow of 10 to 15 cm/sec in the winter, and a southerly flow of 5 to 10 cm/sec the remainder of the year.

Other methods have been employed to detect the magnitude and direction of surface water movement in Monterey Bay. McKay (1970) and Smith (1972) used the geomagnetic electrokinetograph (GEK) to determine instantaneous surface current profiles in the bay. Both found surface currents to be highly dependent on time and position, ranging from 4 to 25 cm/sec. Neither found a high correlation of surface currents to the wind or the tides, although there appeared to be some relation with the tide in the area of the submarine canyon. No distinct circulation patterns were observed, as velocities and directions were different each day the GEK was used.

Others (Smith 1968, Shaffer 1973, Sonu et al. 1963) have viewed the wind as a major driving force of nearshore circulation. Unfortunately, the physics of the momentum transfer between the atmosphere and the ocean is not fully understood, and thus there are only indirect and approximate methods of determining the wind stress on the sea surface. The model is also complicated by the effect of diurnal winds (Shaffer 1973). Coastal circulation is thereby apparently altered by the wind, the offshore oceanic circulation, bottom topography, and the tides, and is thus generally more complex than open ocean circulation. In this study, no attempt has been made to distinguish between these different factors and their role in altering current patterns in Monterey Bay; however, a strong correlation will be demonstrated between the apparent direction and speed of drift cards and the local winds.

CHAPTER 2

METHODS

Olson-type drift cards (Olson 1951, Duncan 1965) (Fig. 3) were utilized in this study. They consisted of a postcard (9.5 x 15 cm) sealed in a 0.6 mm thick polyethylene bag. Postage was prepaid, but no rewards were offered for returns. Each bag was weighted with a 3/8 inch washer so that about 1 cm of the bags floated above water level.

Cards were released monthly at 20 to 33 stations in the Monterey Bay (Fig. 4). The number of cards released and the release stations varied somewhat from month to month to coincide with the hydrographic sampling stations. Between 5 and 20 cards were released at each station, and the total number of cards released each month varied between 100 and 200. Shipboard wind was measured by 100-second hand held anemometer readings. Because of the inaccuracy of the discontinuous shipboard measurements, the most useful wind data were those made at an altitude of 60 m by the Pacific Gas and Electric Company at Moss Landing. Daily average winds were determined by vectorially averaging these hourly data, and progressive vector diagrams were constructed from the hourly values.

Upon return of the drift card, the area of recovery was recorded and a straight line distance from the release point to recovery point was used to calculate the drift speed. This obviously underestimated the true drift speed, because the card may have been beached for some

Sender ______________________

Address ______________________

____

FIRST CLASS
Permit No. 2
Moss Landing, Ca.

BUSINESS REPLY MAIL

NO POSTAGE STAMP NECESSARY IF MAILED IN THE U.S.

POSTAGE WILL BE PAID BY–

MOSS LANDING MARINE LABORATORIES
of the California State Colleges
P.O. Box 223
Moss Landing, California 95039

ATTENTION: Dr. Broenkow

OCEAN CURRENT SURVEY

Location of card where found: ______________________

____

____

Date Found: ________ ______________ 19____
Time Day Month Year

Card was Found: On Beach [ ] In Water [ ]

Bag was Found: Punctured [ ] Water Tight [ ]

REMARKS: ______________________

____

____

Your assistance will help us determine the movement of ocean currents in Monterey Bay. Thank you.

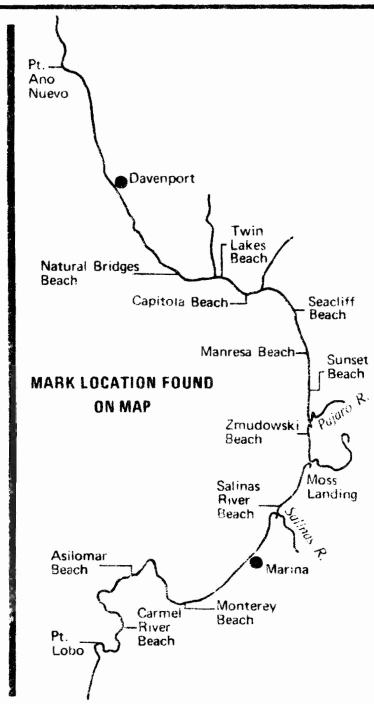

Figure 3. Olson-type drift card, which was sealed in a 0.6 mm thick polyethylene bag weighted to float with less than 1 cm above the water surface.

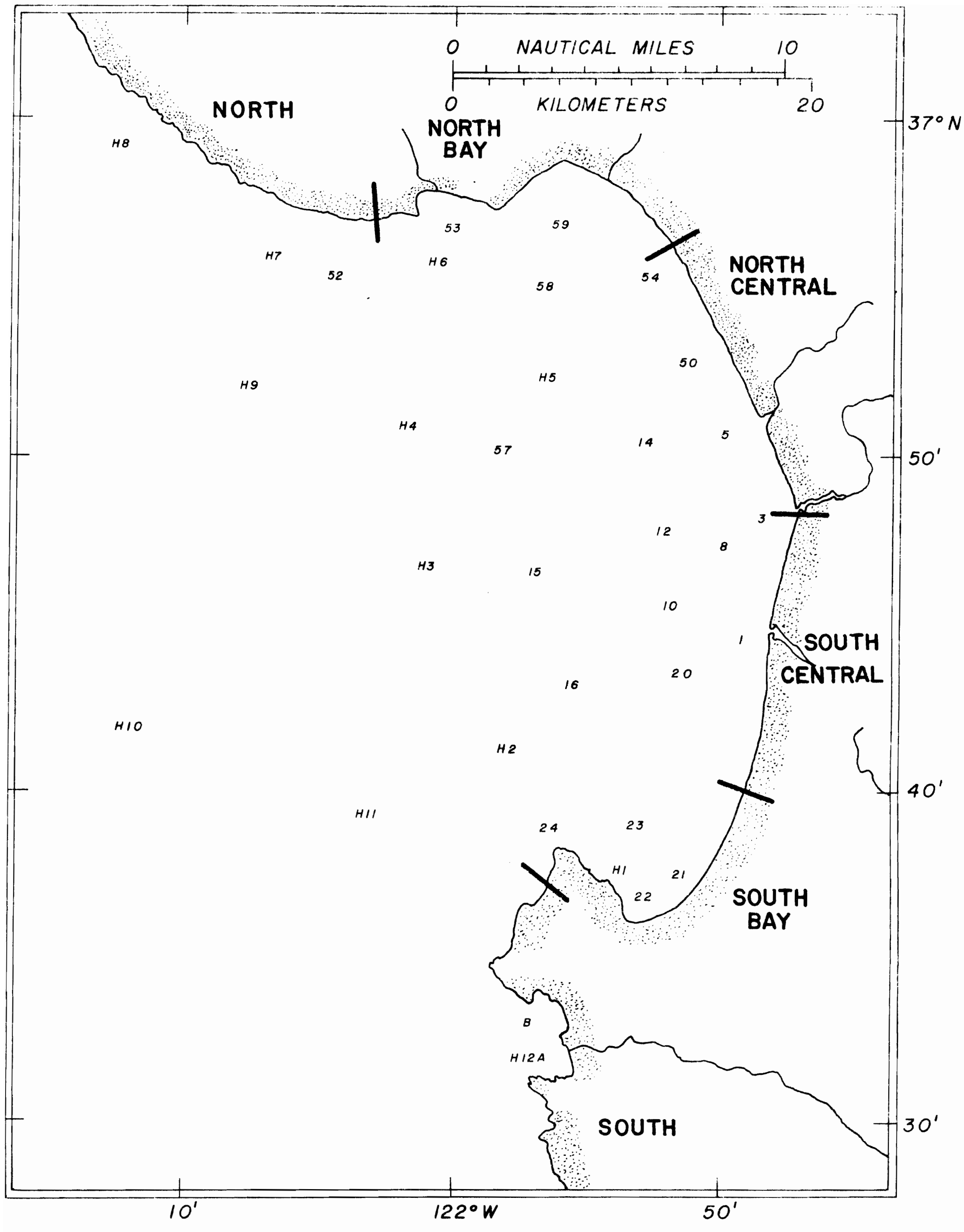

Figure 4. Drift card release stations (numbers) in Monterey Bay. Recovery areas (between bars) refer to data in Fig. 6.

time, and the straight line distance was probably not the true drift path. Out of the cards originating from the same station of release and discovered in the same coastal strip, the date of the first card to be discovered was used to calculate the speed of the entire group.

To estimate the time a card may have spent lying on the beach prior to discovery, two "bogus" releases (Riley 1972) were made, in which drift cards were scattered on ten different beaches within 200 m of an obvious landmark. Both bogus releases were made at night to insure that all cards would be subject to discovery at the same time. During the first bogus release, on a Thursday, cards were placed directly on the beach above the high tide mark and during the second, on a Friday, cards were thrown into the surf zone at an evening low tide. Recoveries from the bogus releases were used to estimate the discovery lag time, the reported position accuracy, and possible transport of drift cards by longshore currents. During a 24-hour parachute drogue study, drift cards were released periodically in mid-bay to examine the diurnal wind and tidal effect on drift card recoveries.

CHAPTER 3

RESULTS AND DISCUSSION

In the following discussion, drift card returns will be related to both oceanic currents and to the wind. An estimate of the effect of human factors influencing drift card data will be made. An analysis of the seasonal variations in drift card returns and similarities to variations in flow patterns of the California Current system will be presented, followed by a comparison of the drift velocity and the wind velocity. And finally, the relation between the velocity of the wind and the movement of the surface waters in Monterey Bay will be expressed as the wind factor.

Charts showing the drift card release and recovery points are presented in the Appendix. The trajectories shown on these maps of course do not represent the true paths, and the recovery areas may only be approximate to simplify drafting. Progressive vector diagrams show the wind conditions at Moss Landing during the first few days when the drift cards were at sea. On these diagrams the length scale has been reduced to 3% to reflect the fact that surface waters move at about 3% of the wind speed as explained later.

Per Cent Return

Over the 20 month period, September 1971 through April 1973, 5478 Olson-type drift cards were released in Monterey Bay and 1253 were eventually recovered along the west coast of the United States, resulting in a mean recovery rate of 22.9%. Schwartzlose (1963), using drift bottles, reported a recovery rate of 4.6% over a five and one-half year period along the western coast of the United States. Dodimead and Hollister (1962), using drift bottles off the coast of Oregon and Washington, reported a return rate of 6.1%, while Wyatt et al. (1972), during a ten year study, found a return rate as high as 33% for a station 5 miles offshore. Griggs (1974) released sea-surface drifters within 3 miles of the Monterey Bay coast and recovered 33%. During the course of this study, 42% of those drift cards recovered were released from stations more than two miles offshore, while the remaining 58% were from those stations within two miles of the coast.

The percentage recovery of drift cards was greatest during the summer with the maximum recovery rate (56%) occurring in September 1972 (Fig. 5). The recovery rate increased from the early spring through the late summer, then dropped to its lowest in November and December of both years (Fig. 5 and 6). Apparently, changes in the wind and current field are reflected somewhat in the recovery rate. The spring and summer months are typically characterized by winds from the north-northwest and surface water moving southeastward (Bolin and Abbott 1963). The winds slackened during the fall and became southerly in the winter, when the currents generally flow northward. During the winter months, more cards were recovered on the northern shores of the bay than during the remainder of the year when virtually all cards were found on the

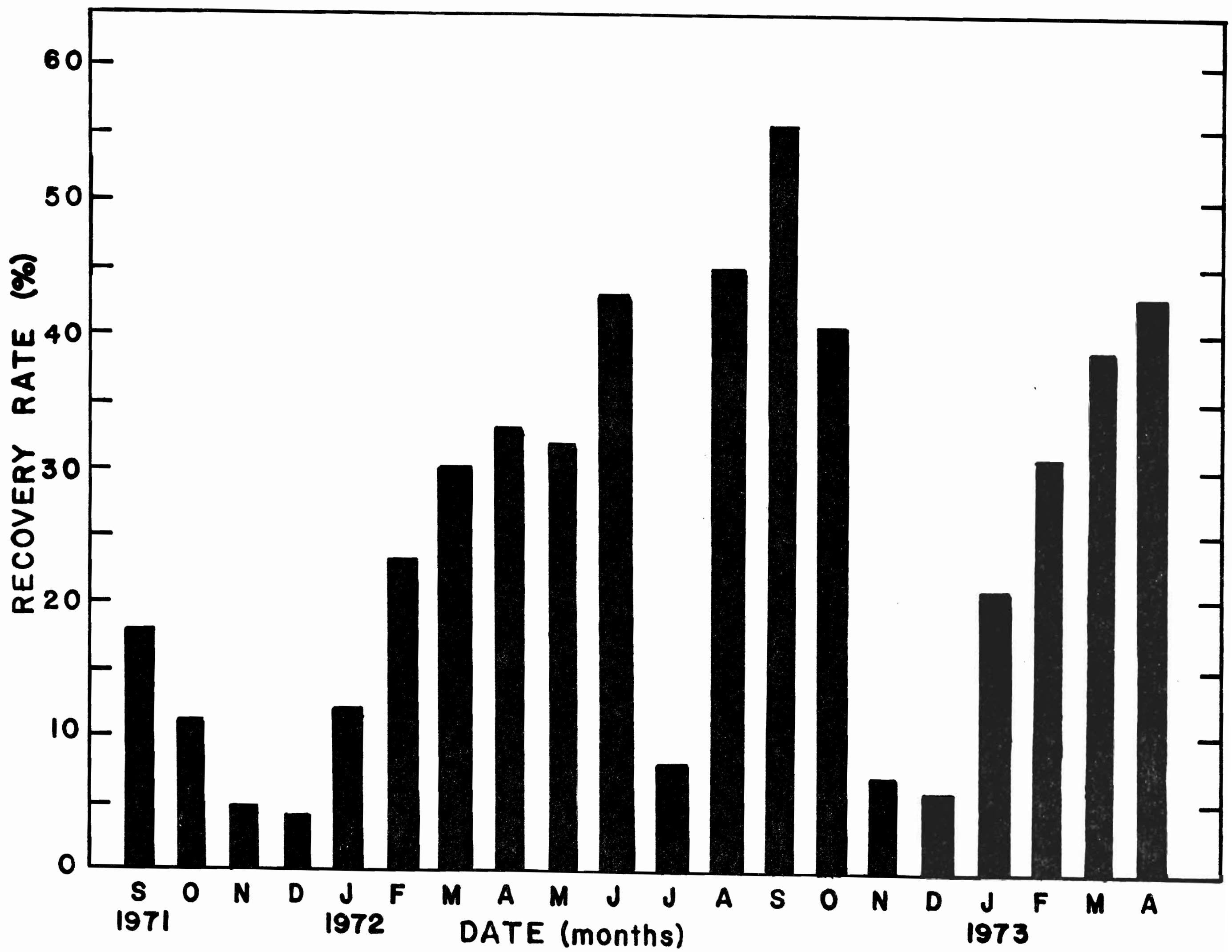

Figure 5. Monthly variation of drift card recovery rate (%).

central and southern beaches (Fig. 6). The movement of surface water, as indicated by drift cards, is then apparently dependent on seasonal changes in both the wind and current. Thus the distribution of substances floating on the sea surface may be influenced largely by the wind.

Open Water Recovery

In estimating the path followed by the drift card from the point of release to the point of recovery, a large error can be made in the use of the straight line approximation, which represents the simplest and shortest path possible. Open water recoveries would have proved invaluable in substantiating this estimation; however, only one card was recovered at sea. During September 1972, a card was found in the central bay which had been at sea for nine days. Other cards released from the same station were recovered over a wide range of the coast (23 km), with the open water recovery illustrating a path midway between the estimated paths of other cards released from that station (Fig. 7).

Long Distance Drifts

While most cards were recovered within Monterey Bay, several were recovered in areas quite distant from the bay, as far north as Westport, Washington, and as far south as Los Angeles, California. Long-term drifts (those cards found outside the area from San Francisco to Point Lobos) (Fig. 8, Table 1) provide an excellent estimate of the nearshore currents on the eastern boundary of the Pacific Ocean. Northward drift

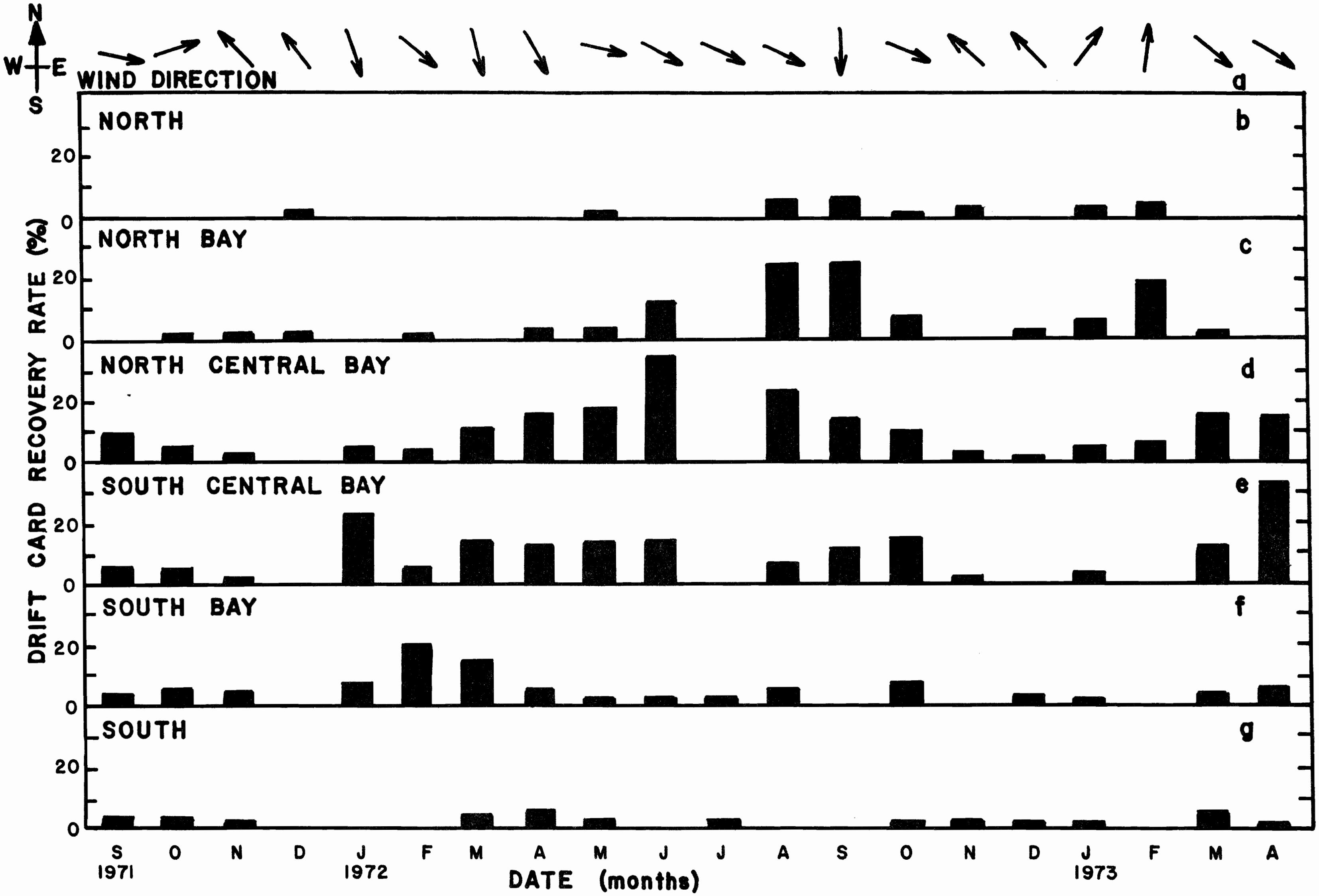

Figure 6. Area of drift card recoveries as the per cent of the total number released per month. Refer to Fig. 4 for location of recovery areas. Wind directions represent the vectoral average of 7 days following drift card release.

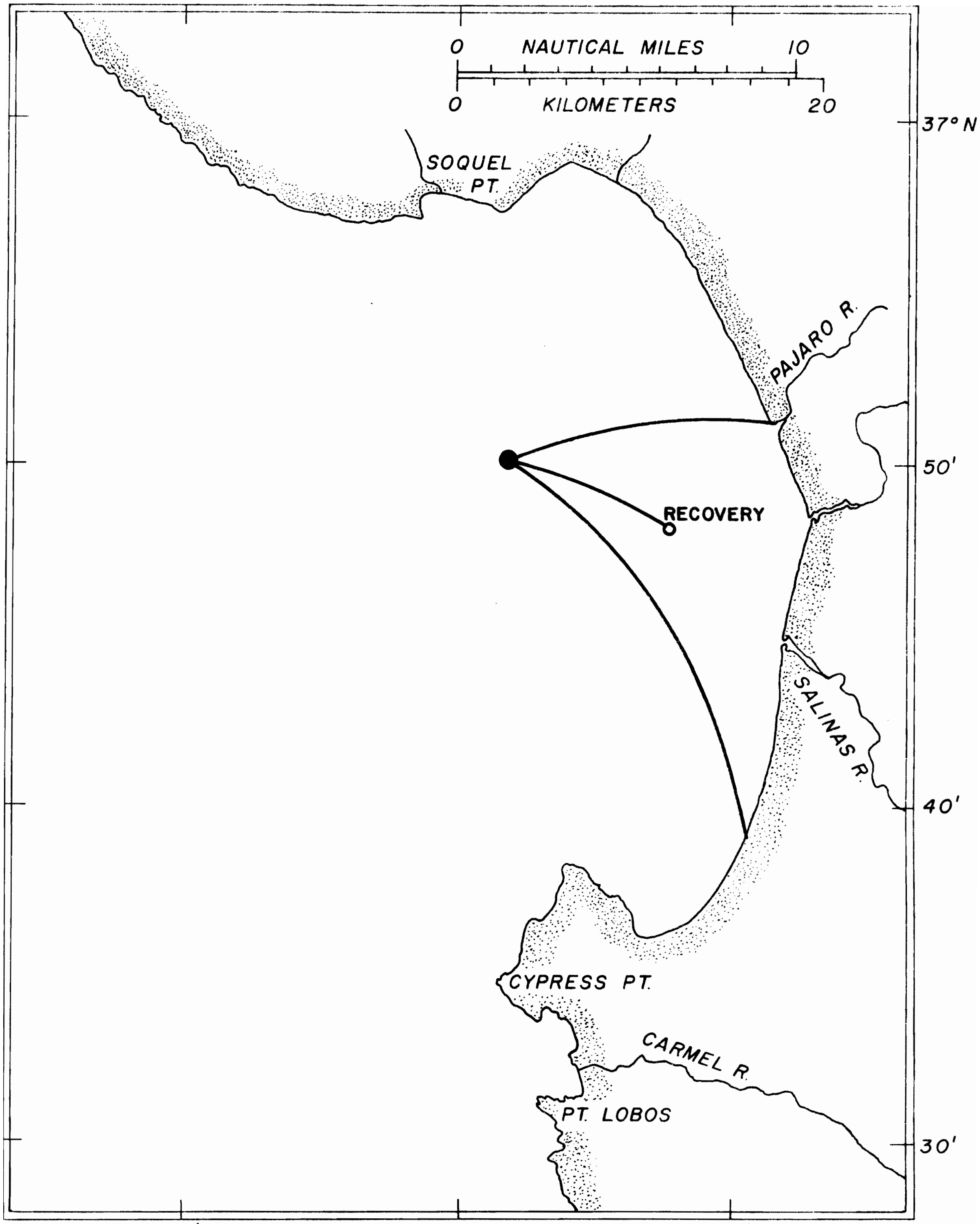

Figure 7. Open water recovery of a single drift card in September 1972.

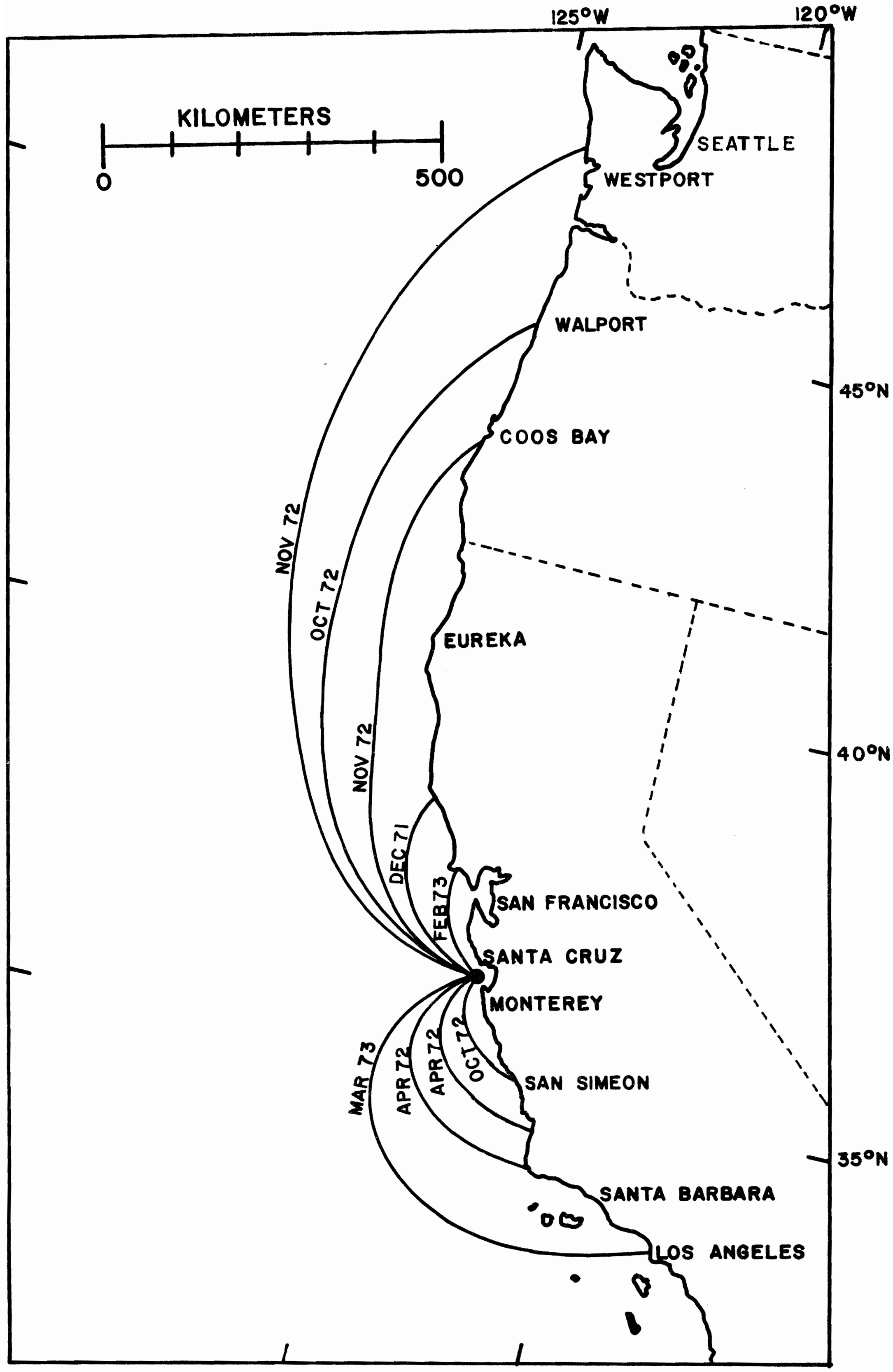

Figure 8. Extreme northward and southward movements of drift cards from Monterey Bay and the month of release.

TABLE 1

LONG-TERM DRIFTS OUTSIDE THE IMMEDIATE VICINITY OF MONTEREY BAY

Month	Area of Recovery	Days Out	Velocity (km/day)	Drift Direction
December 1971	Pillar Point	10	10	N
	Point Reyes	8	10	N
April 1972	Morro Bay	16	14	S
	Oceano	33	7	S
	Pismo	163	1	S
	Vandenburg	23	13	S
August 1972	Point Sur	80	1	S
October 1972	San Simeon	30	5	S
	Walport, Oregon	150	7	N
November 1972	Coos Bay, Oregon	48	8	N
	Westport, Washington	120	5	N
January 1973	Point Reyes	50	4	N
February 1973	Point Reyes	50	4	N
March 1973	Los Angeles	60	6	S

will be assumed to indicate the presence of the Davidson Current reinforced by southerly winds, and a southward drift will be assumed to typify the flow during the upwelling season, which is initiated and maintained by northerly winds (Smith 1968).

The month of October provided the most complex flow pattern with cards released from the same station being recovered at both San Simeon to the south and Walport, Oregon to the north at velocities of 6 cm/sec and 8 cm/sec respectively. October is apparently the month of transition between the northerly winds of summer and the southerly winds of winter. In November 1972 cards were recovered only to the north of Monterey Bay. Presumably the northerly flow continued through February 1973 and ended with the southerly flow of March and the advent of the upwelling season. The recovery of one card in Los Angeles in March 1973 is consistent with the normal southerly flow of the California Current system during the spring upwelling months.

Movement of Drift Cards within Monterey Bay

The behavior of drift cards in the California Current system is distinctly different from those cards recovered within the immediate vicinity of Monterey Bay, largely due to the influence of diurnal winds in nearshore areas. In the following discussion, the relation between the coastal wind, deep water circulation, and the movement of surface water will be examined.

Except for July 1972, the mean monthly drift card speeds (Fig. 9) and recovery rates (Fig. 5) were significantly correlated at the 95% confidence level (r = 0.71). The months of November and December are those of both the lowest mean monthly speeds and recovery rates, while the early spring and summer months show increasing recoveries and speeds. Generally, during the winter months, the wind is from the south with relatively low velocity (Smethie 1973), whereas the winds of the summer months are from the north-northwest with the highest mean daily velocities of the year. Cards released during the winter were apparently moved slowly seaward, resulting in a lower per cent return than during the remainder of the year when northwest winds moved the cards directly ashore (Appendix).

It appears then, that the winds of higher velocity strongly influence the movement of drift cards and surface water, resulting in a quicker delivery of cards to the beach areas where they are discovered. Because the drift cards have a finite lifetime (perhaps two weeks), this results in a direct correlation between recovery rate and mean drift speed. Conversely, the slower winds of fall and winter do not influence the movement of the surface water proportionally. Thus when wind speeds are low and are blowing offshore, the Davidson Current and local circulation patterns appear to be the principal driving force of surface water.

The apparent divergence of drift cards in May, August, and September 1972 (Appendix) in the north section of the bay would appear to represent a counterclockwise gyre (Garcia 1971) which has been partially sub-

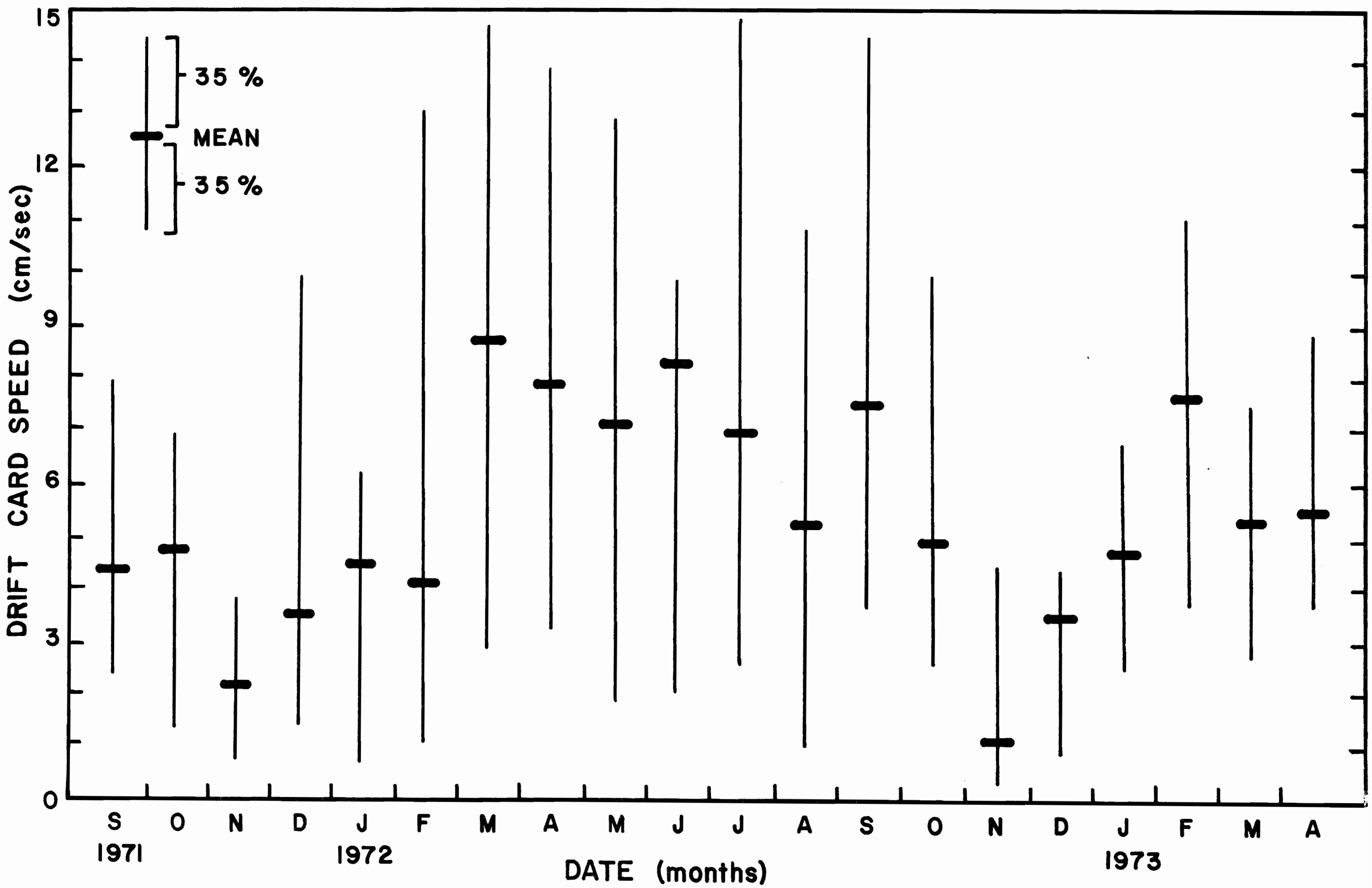

Figure 9. Drift card speeds in Monterey Bay, given as the mean speed ± 35% of the observed speeds.

stantiated by drogue studies. However, since the drift cards were not recovered sequentially around the north bay periphery, these data are not sufficient in themselves to demonstrate the presence of counter-clockwise circulation in the north bay. It is postulated that the observed distribution resulted primarily from the effect of the diurnal wind (Fig. 10).

Geostrophic Current, Wind, and Drift Direction

Mean monthly surface current directions just offshore from Monterey Bay were estimated from the 15-year dynamic topography charts of Wyllie (1966). During many months the inferred geostrophic currents compare favorably to the direction of drift card movement and to the mean wind direction within Monterey Bay during this study (Table 2). Dodimead and Hollister (1958) observed the drift bottle paths to parallel geo-potential isobars. Some trans-isobaric transport occurred, possibly due to the wind. Others (Chew *et al.* 1962, Brucks 1971, Tibby 1937) have found geostrophic currents, thermocline topography, and drift bottle data to be similar with some exceptions where the wind was suspected of altering surfact water transport.

The early spring and fall appear to be periods of transition between the northerly winds of summer and the southerly winds of winter, and the respective changes which occur in the mean drift direction and the geostrophic current direction. It is felt that the latter two result from the local wind field and that they can be anticipated by

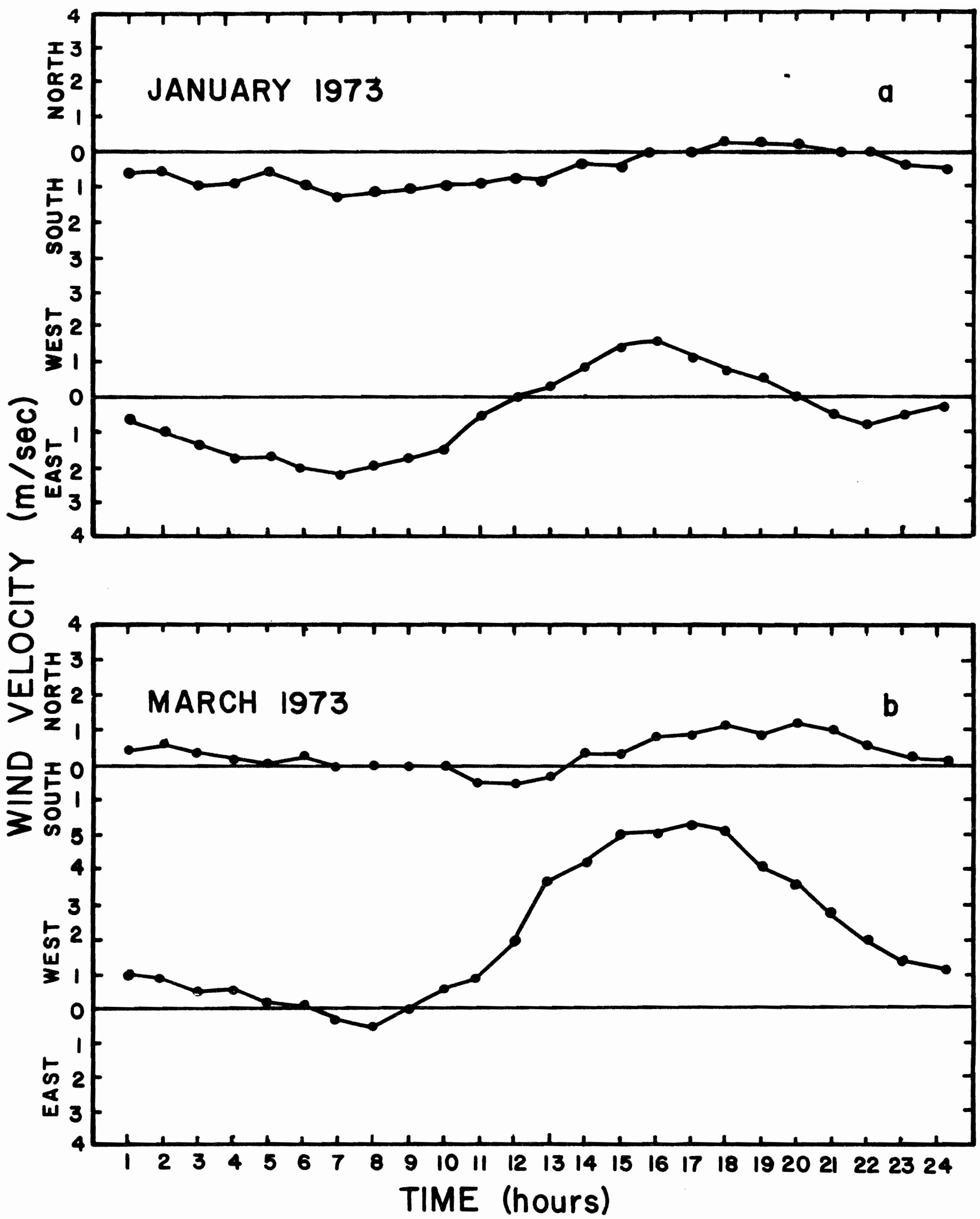

Figure 10. Monthly mean winds at 60 m height at Moss Landing, California, from (a) 1-31 January 1973, and (b) 1-31 March 1973.

TABLE 2

A COMPARISON OF THE GEOSTROPHIC CURRENT (FROM WYLLIE 1966), WIND, AND DRIFT CURRENT DIRECTIONS IN THE VICINITY OF MONTEREY BAY OBSERVED IN THE PRESENT STUDY

Month	Geostrophic Direction	Drift Direction	Wind Direction
January	N	N	S
February	S	N	S
March	N	S	N/W
April	S	S	N/W
May	N	S	N/W
June	N/E	E	N/W
July	E	E	N/W
August	N	E	W
September	N	N/E	S/W
October	N	S/E	S/W
November	N	N/E	S/W
December	N	N	S

observing changes in the wind field. The estimation of the response of the surface waters to the wind is therefore an examination of the transfer of energy from the wind to the large volumes of water in the ocean. This is generally observed in the form of upwelling and the Davidson Current off California. Another dimension is therefore added to the importance in understanding the response of surface waters to variations in the wind field. The drift patterns established from the use of drift cards results not from the predominant oceanic current, but primarily from the momentum transfer by the wind to the ocean. It will be demonstrated that as the force of the wind diminishes, as typically occurs during periods of transition, its stress becomes less until it does not affect significantly the surface layers.

Surprisingly, there was some agreement between parachute drogue and drift card velocities and directions during the AMBAG study year (Table 3). Thus the movement of the surface layer (the upper 20 cm in which drift cards float), although wind driven, may be indicative of deeper currents in Monterey Bay. With the exceptions of August and September, drogues were not deployed throughout the bay, thus not allowing for an examination of possible spatial variations in currents. However, current patterns during August and September indicate some agreement with the gyral circulation postulated by Garcia (1971), which was not detected in the drift card movement. Surface water movement was found to be highly dependent on the wind; however, deep water currents,

TABLE 3

SUMMARY OF THE NET 24-HOUR PARACHUTE DROGUE DRIFT (OSI 1973)

AND DRIFT CARD DATA DURING 1972

Month	Parachute Drogue Direction	Parachute Drogue Speed (km/day)	Parachute Drogue Depth (m)	Drift Card Direction	Drift Card Speed (km/day)
February	E	4	11	N	4
April	S/W	20	12	S	7
May	N/E	7	3	S/E	6
June	E	10	12	E	8
July	E	12	12	E	12
August (South Bay)	E	9	12	E	4
(North Bay)	N/W	9	11		
September (North Bay)	N/W	13	11	N/E	7
(Central Bay)	E	18	11		
(South Bay	W	9	11		

as determined with parachute drogues, apparently are not as immediately influenced by the wind.

Spatial Variations in Drift Card Recovery and Speed

Seasonal variations in drift card recovery rates and speeds were reported earlier in this study (Fig. 5, 6 and 9). Wyatt *et al.* (1972) observed the recovery rate to decrease with the offshore distance of the release area. The mean recovery rate within Monterey Bay varied from 9% for the release areas at the mouth of the bay to 46% of those released within 2 km of shore (Fig. 11a); however, these differences may not be statistically significant due to large month to month variations. The entire nearshore release area resulted in a generally higher recovery rate than those offshore release stations, possible due to the loss of more offshore drift cards caused by sinking. The coastal beaches outside of Monterey Bay are also less accessible than within the bay, resulting in a low recovery rate of cards to the immediate north and south of the bay.

Drift card speeds were spatially uniform throughout the bay (Fig. 11b) with no significant differences being noted. Thus surface drift speeds observed in one area of Monterey Bay may be indicative of speeds throughout the bay.

Time at Sea

As the reliability of drift card data is determined by the accuracy

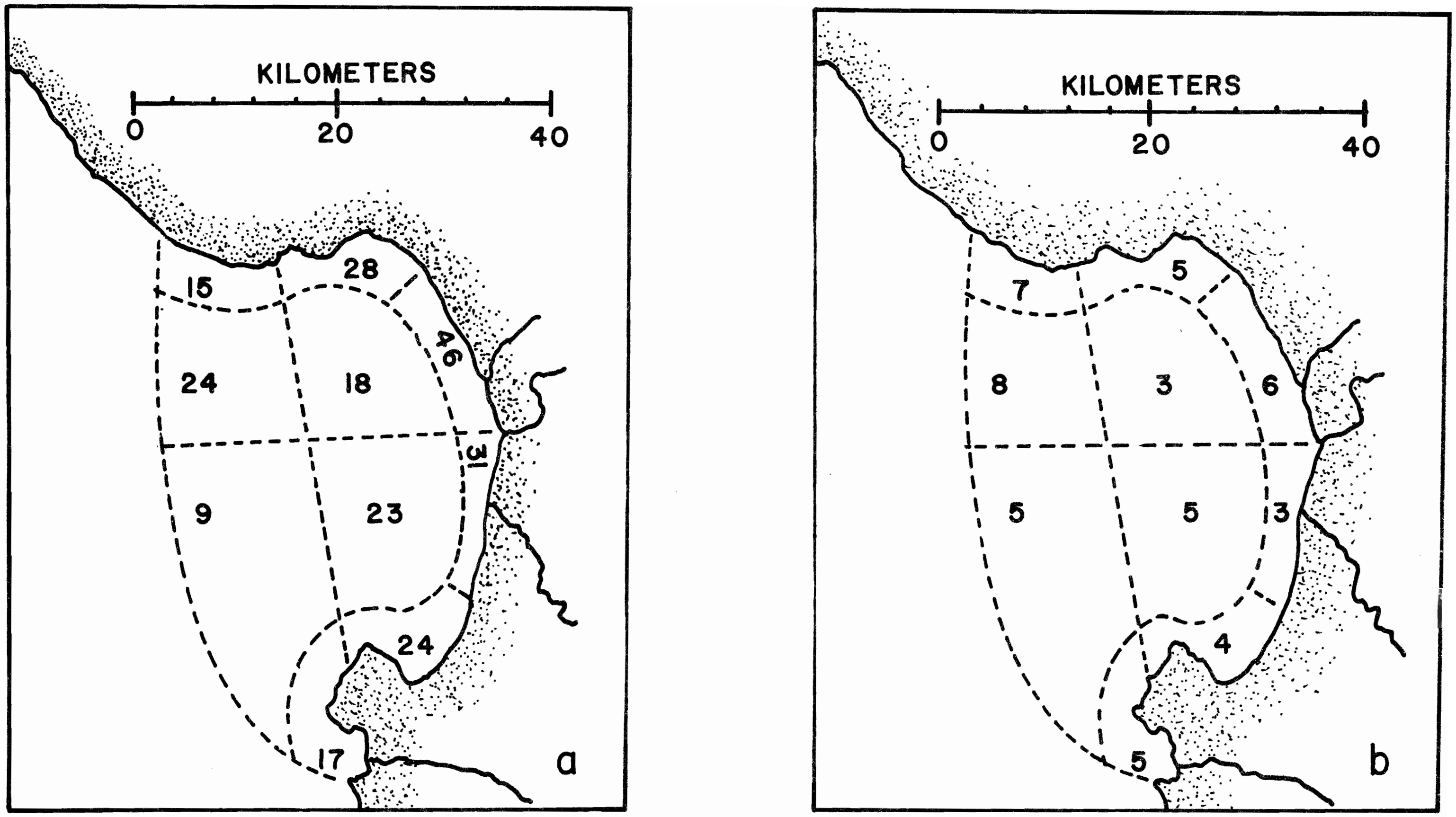

Figure 11. Spatial variations of (a) mean per cent recovery and (b) mean speed of drift cards (km/day) by sector for the entire period of study.

of people returning the drift cards, it is necessary to estimate the bias and error introduced into the data by human factors. The frequency with which beaches are visited may be one source of bias since a card beached early in the week may remain undiscovered until the next influx of visitors on weekends. Wyatt et al. (1972), working off the coast of Oregon, detected a weekend bias in the recovery of drift bottles along the California coast. In this study, 22.4% of the cards returned were found on Saturdays, 16.9% on Sundays, and only 8.9% on Wednesdays, the day of the lowest number of finds (Fig. 12). Sixty-eight per cent of the cards returned were found within seven days of their release (Fig. 13); however, two peaks in the discoveries were observed, at two and at nine days. These are apparent harmonics of one another and, being separated by seven days, also indicate the weekend bias for discovering drift cards.

In November 1971 and April through August 1972, drift cards were released on Mondays, Tuesdays, and Wednesdays. With the exception of November 1972, all other releases were on Wednesdays, Thursdays, and Fridays, which was generally during the winter months. Although the weekend bias was more significant for those cards released on Wednesdays, Thursdays, and Fridays (Fig. 13b, c), many of the cards released on Mondays, Tuesdays, and Wednesdays were recovered 3 to 4 days later, apparently on a weekend (Fig. 13a). The weekend bias appears to be more significant during the winter (WTF releases) when beaches are more heavily visited on weekends, than during the summer (MTW releases) when beaches are occupied throughout the week. Although these data do

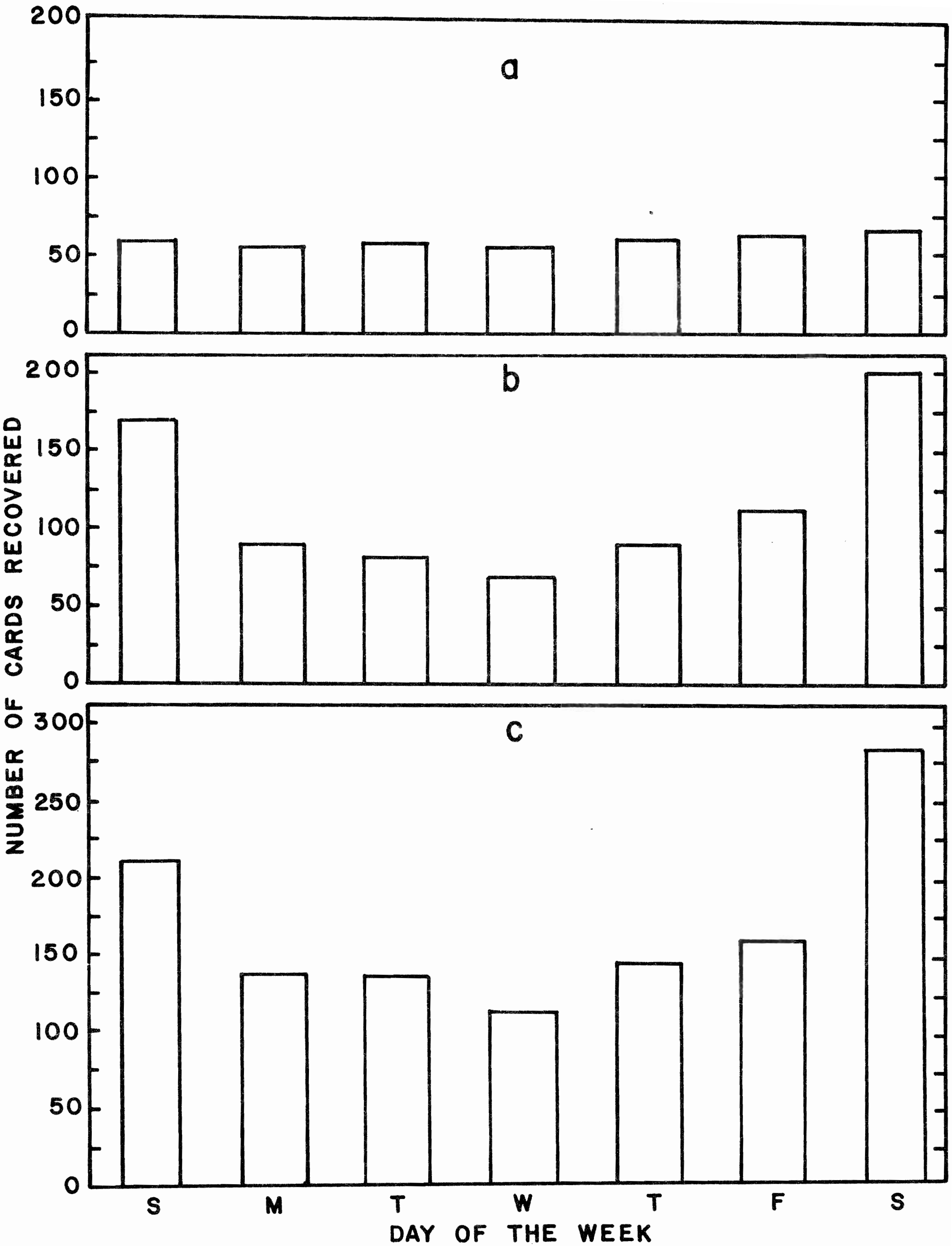

Figure 12. Day of the week on which drift cards were recovered for (a) all cards released on Mondays, Tuesdays, and Wednesdays, (b) all cards released on Wednesdays, Thrusdays, and Fridays, and (c) for all cards during the entire period of study.

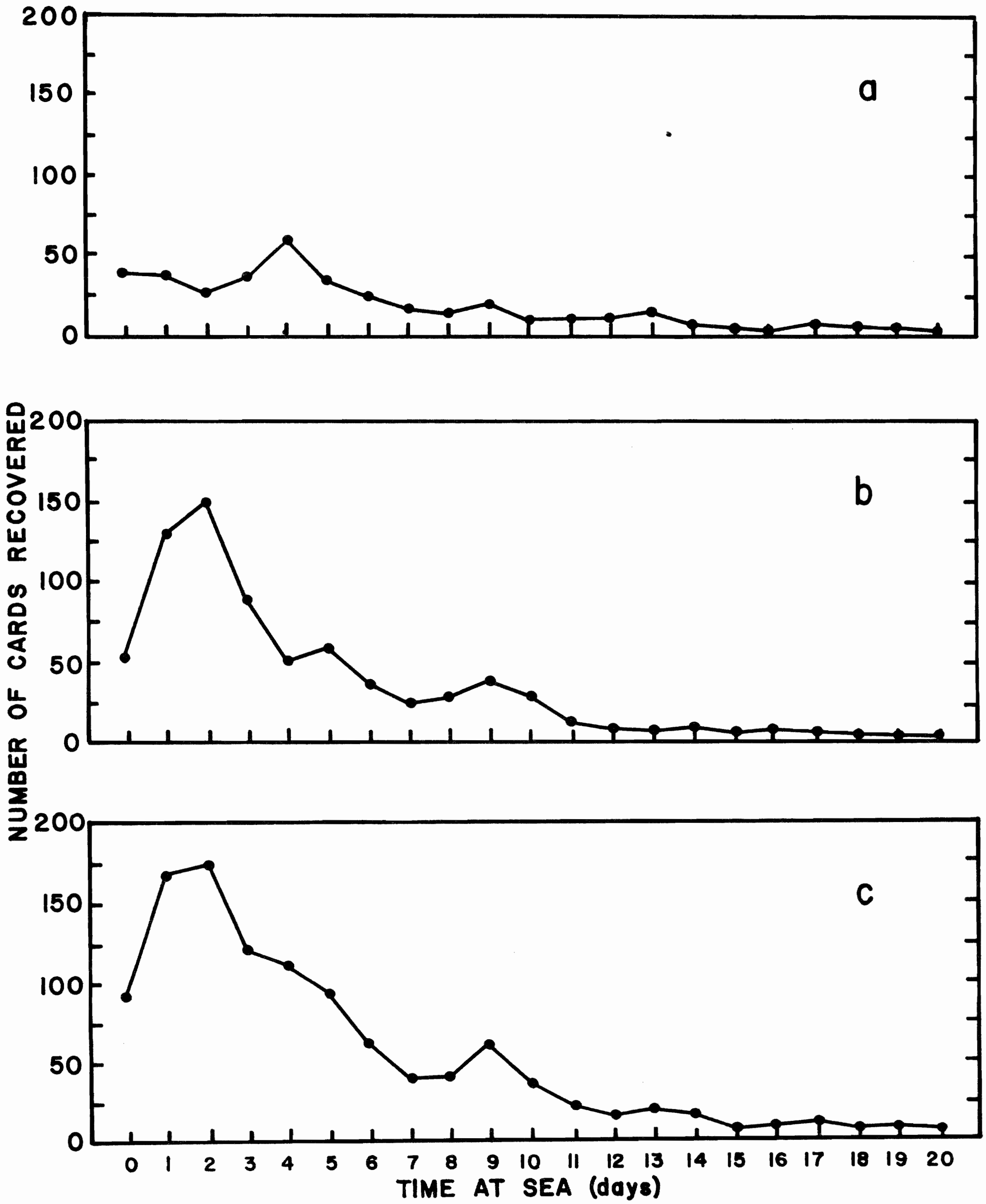

Figure 13. Apparent time at sea for drift cards released (a) on Mondays, Tuesdays, and Wednesdays, (b) on Wednesdays, Thursdays, and Fridays, and (c) during the entire period of study.

not clearly indicate whether the weekend bias is a function of the day of release, or the season in which drift cards are released, it is felt that the latter is more significant in producing a weekend bias due to the high number of tourists during the summer.

Bogus Releases

With the exception of two obviously false returns, which were reported as being found in Seattle, all positions of the bogus release cards were reported within 0.6 km accuracy, while most were reported more accurately than this. The second bogus release indicates that cards thrown into the surf zone were not moved by longshore currents.

The apparent "time at sea" was calculated as the time elapsed betweel midnight and the hour of recovery, and the finders of the cards indicated reasonably precise recovery times. Cards released on Friday were found in higher numbers and more quickly than those cards released on Thursday (Fig. 14), possibly due to the weekend bias in card recovery. Although these bogus data indicate that not all cards will be recovered immediately, they demonstrate that most cards will be found within one day after being beached. These data corroborate the assumption that when two or more cards from the same station are recovered in the same coastal sector, the shortest time at sea can be assumed to represent the true time at sea for the entire group.

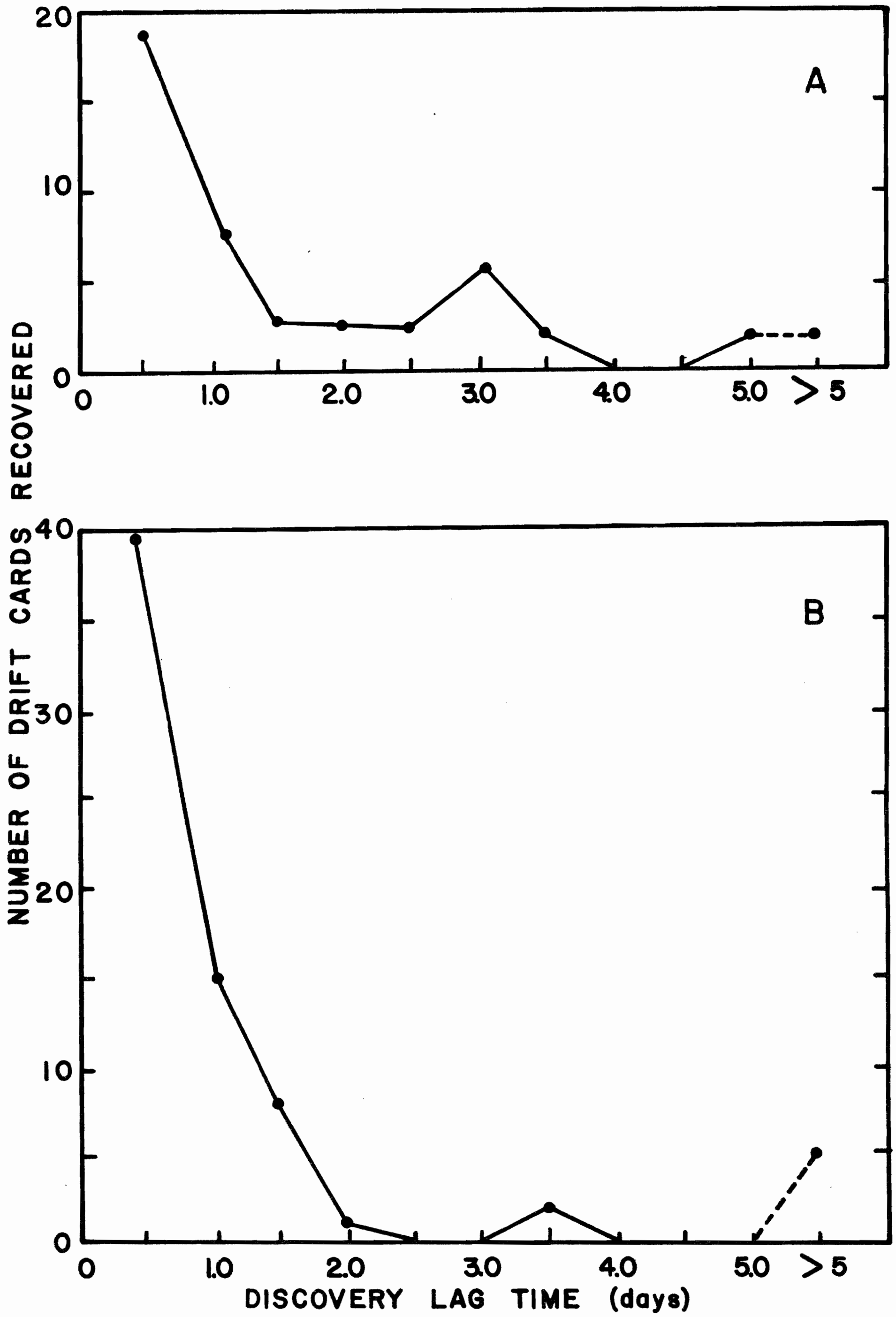

Figure 14. Discovery lag time estimated from bogus releases on a (a) Thursday, 13 September 1973, and (b) Friday, 28 September 1973.

Twenty-Four-Hour Study

Riley (1972) examined the effect of tides on the behavior of drift cards in nearshore areas and concluded that tidal effects were insignificant. During a 24-hour parachute drogue study in central Monterey Bay in July 1973, drift cards were released periodically throughout the day near the moving drogue. All recoveries were made in north central and central beach areas (Fig. 15), over a range of about 18 km. Although specific recovery areas shifted during the 24-hour survey, no obvious relation between the semi-diurnal tide and the recovery area was noted. Rather, there appeared to be a direct relation to the diurnal shift in the velocity and direction of the coastal winds (Fig. 15).

Evening winds transported cards northward, while the mid-day winds, of higher velocity, quickly pushed the cards ashore in a nearly straight easterly direction. Recovery data from the 24-hour study indicate a very short response time of the surface drift current to a change in the velocity and direction of the wind. One should specifically note the difference in the apparent paths of those cards released at 1730 and 2400 hours and the respective changes in the wind field (Fig. 15). The wind was southerly at 1730 and a northerly transport of drift cards was observed, whereas at 2400 the wind was beginning to shift to a west-northwest direction resulting in an easterly transport of the cards. Thus the diurnal wind appears to be as significant as the seasonal wind in determining the movement of surface water.

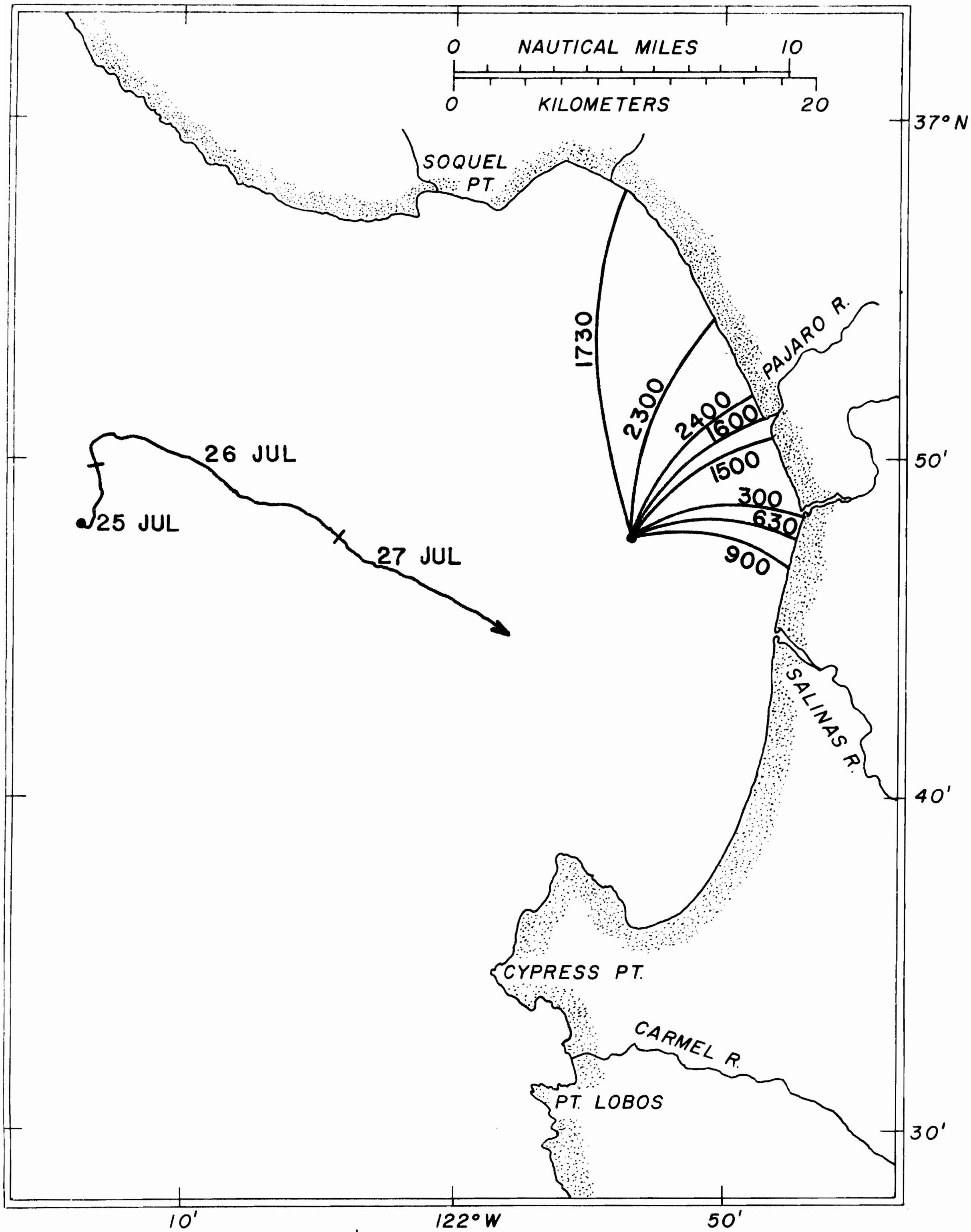

Figure 15. Inferred drift card paths during a 24-hour period, July 1973. Insert shows the progressive wind vector reduced to a 3% scale between 1500, 25 July and 2400, 27 July.

Wind and Drift Direction

The assumption has been made in previous studies (Hamby 1964, Tomczak 1964) that the difference between the surface drift and the wind direction is 0°. To estimate the reliability of this assumption, the seven-day wind directions representing the time at sea for a majority of the drift cards were compared to the general drift card directions. Good agreement was found when the wind velocity was greater than about 1.0 m/sec. During September and December 1972 and January 1973 when the mean wind velocities were less than 1.0 m/sec, the drift direction did not closely agree with the wind, but followed the presumed northerly flowing Davidson Current. Wind velocities less than 1.0 m/sec apparently exert little influence on the surface currents, at which time oceanic circulation becomes a more important factor in the movement of surface waters. Hachey (1953) found the direction and magnitude of the surface currents to be strongly influenced by the force and direction of the wind when it exceeded 5 m/sec.

Drift Current Speed

Mean drift card speeds have been calculated using the straight line distance between the station of release and the area of retrieval. However, the actual drift route probably does not consist of a straight line, and the time at sea would be somewhat less than observed. The resulting mean drift card speeds would then represent one estimate of minimum drift current speeds. Tomczak (1964) suggested the drift card is more likely to have a zigzag course corresponding to the changing directions of the wind during the drift time. It is possible that cards are directly affected by the wind. Tomczak (1964) observed during the release of cards under strong wind conditions (>20 m/sec), that the cards were sometimes seized by the wind in the breaking crest of a wave. Therefore, it is felt that the maximum observed drift card speeds may be an overestimation. Consequently, it is felt that the best estimate of the drift current speed is the speed median to the mean and the maximum speeds observed (Fig. 16a). In the following discussion of the wind factor, both the mean speed and the speed median to the mean and the maximum will be examined in relation to the wind.

Wind Factor

Several authors have developed an empirical expression for the wind factor (k) which is the ratio between the surface drift current speed and the wind velocity. In the following discussion, the drift card wind factor for Monterey Bay will be determined and compared to the factors determined in previous studies.

Tomczak (1964) developed a coefficient between the wind velocity at 10 m above the water surface and the speed of the drift current, determined with the use of drift cards and oil. Assuming a 0° difference between the drift current and the wind direction, and that the mean drift speed was probably the minimum speed, he found the speed of the surface layer to amount to 2.9% of the wind velocity. However, a wind factor,

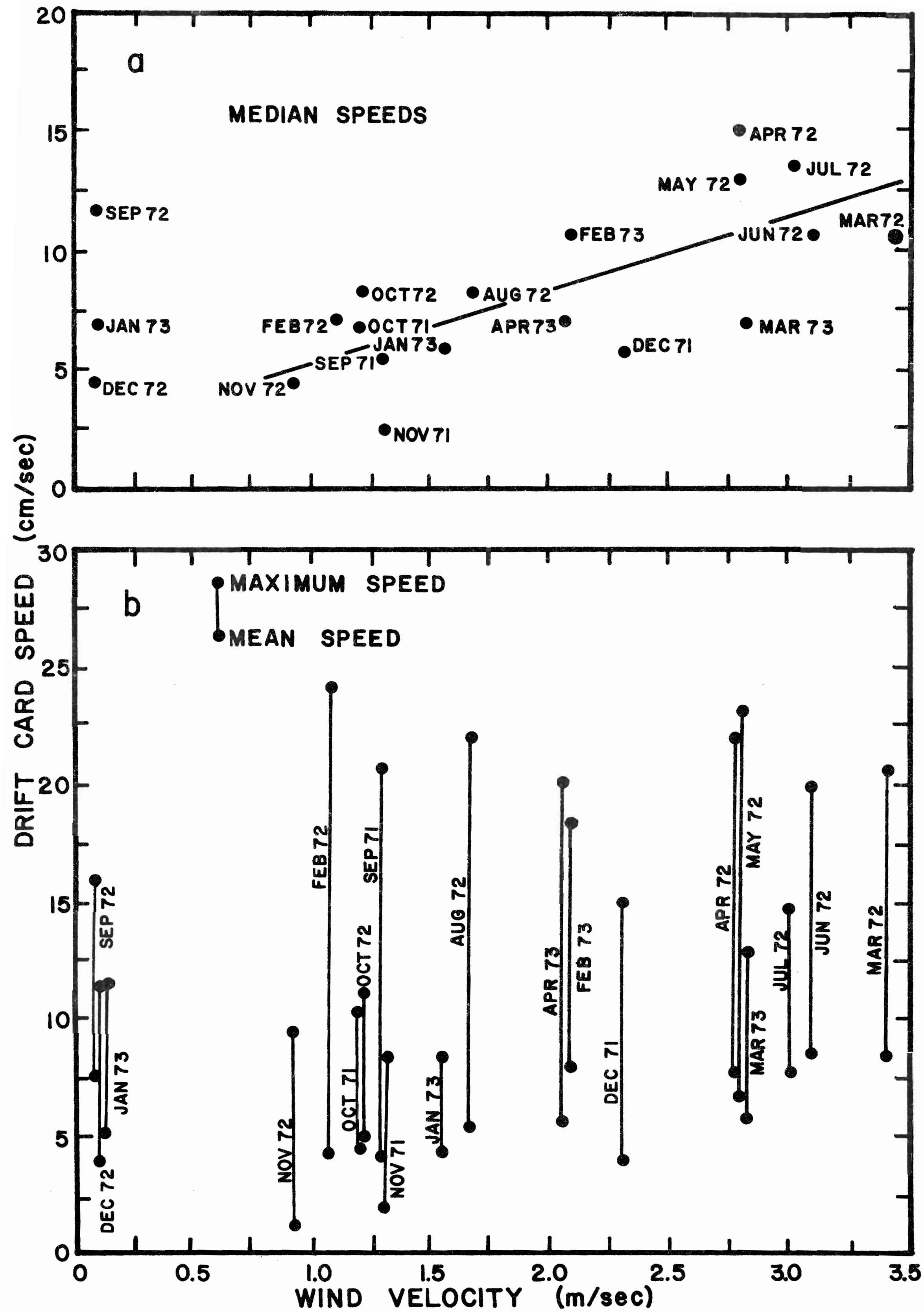

Figure 16. (a) Comparison of median drift card speeds with 7-day mean wind velocity. Line represents the least squares slope discussed in the text. (b) Comparison of maximum and mean drift card speeds with 7-day mean wind speeds.

$k > 2.9$, was statistically ascertained by assuming 16 different k values and comparing progressive vector coast intersections to the actual recovery areas. The evaluation of the drift of nearly 1,000 cards by progressive vector analysis produced the wind factor k = 4.2, which nearly corresponded to that obtained by tracing a large oil patch (k = 4.3).

The least squares regression of mean drift card speed to wind speed when the wind speed exceeded 0.9 m/sec gives a slope of 0.022 (Fig. 16). September and December 1972 and January 1973 were months of low mean wind velocities (less than 0.9 m/sec) and deviate from this moderately good correlation (correlation coefficient, r = 0.82).

The least squares regression of drift card speeds median to the mean and maximum speeds vs. the wind speed results in a slope of 0.030 (r = 0.71), in excellent agreement with Tomczak's (1964) 2.9% wind factor derived from mean drift card speeds. Tomczak (1964), however, adjusted this wind factor to reconcile the progressive wind vector diagrams with drift card returns. This resulted in his acceptance of a wind factor k = 4.2%.

In accordance with Tomczak's (1964) results the 3% wind factor based upon median drift card speeds may be somewhat low. Progressive surface drift diagrams, constructed using a 4% wind factor (Fig. 17), indicate a strong diurnal wind effect and substantial agreement with the observed recovery areas of drift cards. During all months in which the mean wind velocity exceeded 1.0 m/sec routes similar to the inferred

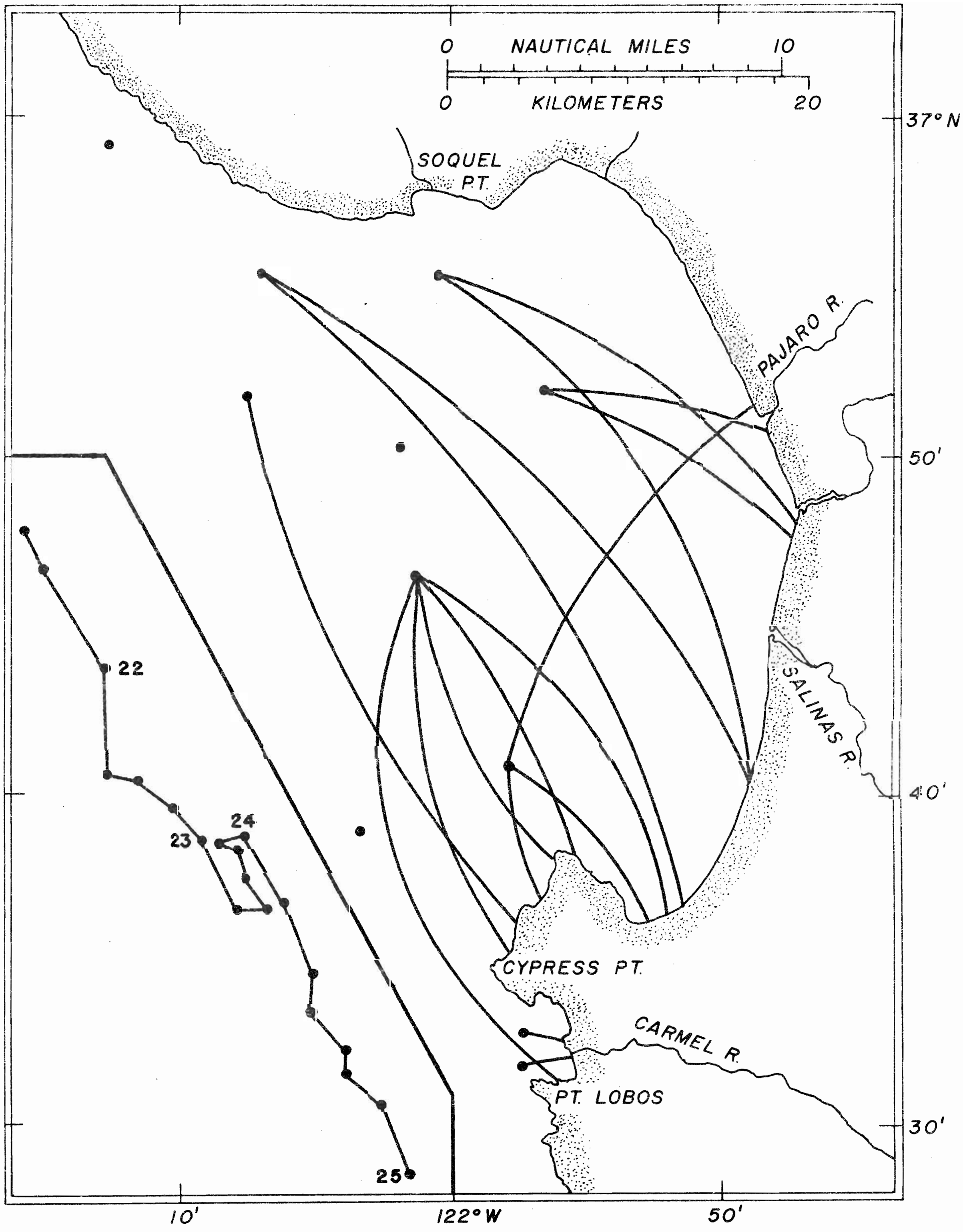

Figure 17. Inferred drift card paths during March 1972. Solid circles without path lines indicate no cards were recovered. Insert shows the progressive drift of cards at 4% of the wind velocity during the indicated day.

drift directions were observed. During those months of lower velocity, the progressive surface drift plots indicated little wind induced movement (Appendix). Thus, in Monterey Bay the wind factor appears to lie between 2.2% (based upon the mean drift velocities) and 4.0% (based on agreement between drift card recovery areas and progressive drift plots). Thus, the 3% wind factor obtained by the regression of drift speeds median to mean and maximum speeds, is apparently reliable and central to the observed range of the wind factor.

When the movement of water to greater depths is considered, as with parachute drogues or other deeper drifters (Table 4), the wind factor decreases, a result consistent with Ekman's familiar model in which current velocity decreases exponentially with depth and rotates cum solar from the wind direction.

It is important to determine the minimum velocity at which the wind factor still holds. The drift card speed apparently was not related to wind velocities less than about 1 m/sec (Fig. 16). When the wind velocity was about zero, the drift speed ranged from about 4 cm/sec to 12 cm/sec (Fig. 16). This indicates the surface water speed may result from the wind and deep water circulation; however, the wind is considered to be the primary force in nearshore circulation when it is greater than 1 m/sec. Deep water current speeds in Monterey Bay have been reported to range from 5 to 15 cm/sec (Smethie 1973); thus the surface water velocity may result from the sum of the current speed and the wind velocity.

TABLE 4

WIND FACTOR "k" AS DETERMINED BY SEVERAL AUTHORS

(FROM TOMCZAK 1964)

Author	k(%)	Method of Determination	Valid For
Hunkins	1.0 to 2.8	Drifting ice floe	Thick surface layer
Thorade	1.44	Drift of ships	Thick surface layer
Ekman	1.85	Current measurements at 5 m depth	Surface to 5 m
Rossby/Montgomery	2.53	Theoretical	"Surface layer"
Stommel	2.9	Drifting buoys	Surface to 1 m
Hughes	3.3	Drift cards	Thin surface layer
Van Dorn	3.6	Experiments in basins	Thin surface layer
Tomczak	4.2	Drift cards	Thin surface layer
Tomczak	4.3	Drifting oil patch	Thin surface layer

Schubert (1973) described the possible movement of an oil spill in Monterey Bay, based upon data from this study, as the vectoral sum of a 3% wind factor and a hypothesized 15 cm/sec tidal current. Schubert's (1973) predictions did not include the important effects of diurnal winds and secondary effects of the general circulation.

Murray (1972) has observed the approximate size and shape of an oil spill to be predictable with knowledge of the current speed, horizontal eddy diffusivity, and the oil discharge rate. He observed the turbulent eddy stresses to act on the slick in the same manner as they acted on floating drift cards, as did Tomczak (1964) and Smith (1973). Thus, in Monterey Bay surface currents, as indicated by drift cards, apparently are the result of both the wind and oceanic circulation, the former being considered more important in this study.

Practical application of the wind factor has been used successfully in estimating the actual path of the drift card resulting from a 4% drift current for the month of March 1973 (Fig. 17). Cards released from a central bay station were recovered within 5 km of the Salinas River three to five days after release. A 4% progressive vector plot (Fig. 17) reveals a diurnal drift path, resulting directly from the wind, which intersects the coast within the observed 5 km range of the Salinas River at three days after release. This indicates a substantial agreement between the applicability of the wind factor and actual drift card results. Thus, the wind factor may be used effectively in estimating the fate of those substances found freely floating on or in the surface water near the coast and under the influence of the diurnal wind.

CHAPTER 4

SUMMARY AND CONCLUSIONS

From September 1971 to April 1973, Olson-type drift cards were used to examine the movement of surface waters in Monterey Bay. During that period about 23% of the cards were recovered, the highest recovery rates occurring in summer. The lowest recovery rates, during the winter months, were also the months of the slowest drift speeds. Changes in the California Current system were detected through variations in the recovery rates and speeds of drift cards throughout the year. Long distance drifts outside Monterey Bay indicate a northerly flowing Davidson Current from October to February at speeds ranging from 5 to 12 cm/sec. No long term drifts were observed between May and August, the normal period of upwelling in the bay area, when the cards were apparently blown shoreward. During the remainder of the year, the southerly flowing California Current was observed at speeds ranging from 1 to 15 cm/sec.

Drift directions usually agreed with the mean geostrophic current and wind directions, indicating surface currents may result from both wind and deep water current movements. Drift card speeds also agreed with drogue speeds and directions, and were spatially uniform throughout the bay. Thus the surficial circulation of Monterey Bay waters appears to be primarily wind driven. The circulation of deeper layers cannot be resolved from this study, except perhaps during periods of low (<1 m/sec) wind velocity.

Drift card recoveries were biased toward weekend discovery, as most cards were found on either Saturday or Sunday. However, it appears that the season during which cards are released is more important in producing a weekend bias than the day of the week on which cards are released. Sixty-eight per cent of the drift cards were recovered within 7 days of their release, indicating most cards were quickly moved ashore and recovered.

Two bogus releases substantiated the reported recovery areas as being accurate, and indicated that drift cards are not moved substantially by longshore currents. During the bogus releases, most cards were found immediately. Thus, of the cards originating from the same station of release and discovered in the same coastal strip, the date of the firstly discovered card can be assumed as the date of retrieval for the entire group of cards. A 24-hour study indicated that tides did not affect the paths of drift cards. However, cards did respond quite readily to the diurnal seabreeze-landbreeze cycle, resulting in significant changes in the direction of the surface drift. Therefore, the diurnal winds may be as important as seasonal winds in determining the distribution of substances floating at the air-sea interface.

It was determined that mean drift card speeds represented the minimum drift speed and that a more representative estimate was the speed median to the mean and maximum speeds observed. This assumption was important in calculating the wind factor, k, which can be used to determine and predict the speed of drifting objects, oil, debris, sewage, and dead animals on the surface waters of Monterey Bay. When the wind speeds were greater than 1 m/sec, the speed of the surface drift current was about 3% of the wind velocity.

The wind factor has been estimated to range from 2.2% to 4%, resulting in an accepted central value of about 3%. Using a progressive vector technique, the 4% wind factor was determined as the maximum reliable value in Monterey Bay. In Monterey Bay, the circulation of the surface layer is primarily wind driven; therefore the movement and distribution of floating substances in the bay will be largely influenced by changes in the diurnal and seasonal wind field. Since it has been established that drift cards and oil behave similarly, drift cards are an important tool to examine the wind driven circulation and its role in distributing pollutants in Monterey Bay.

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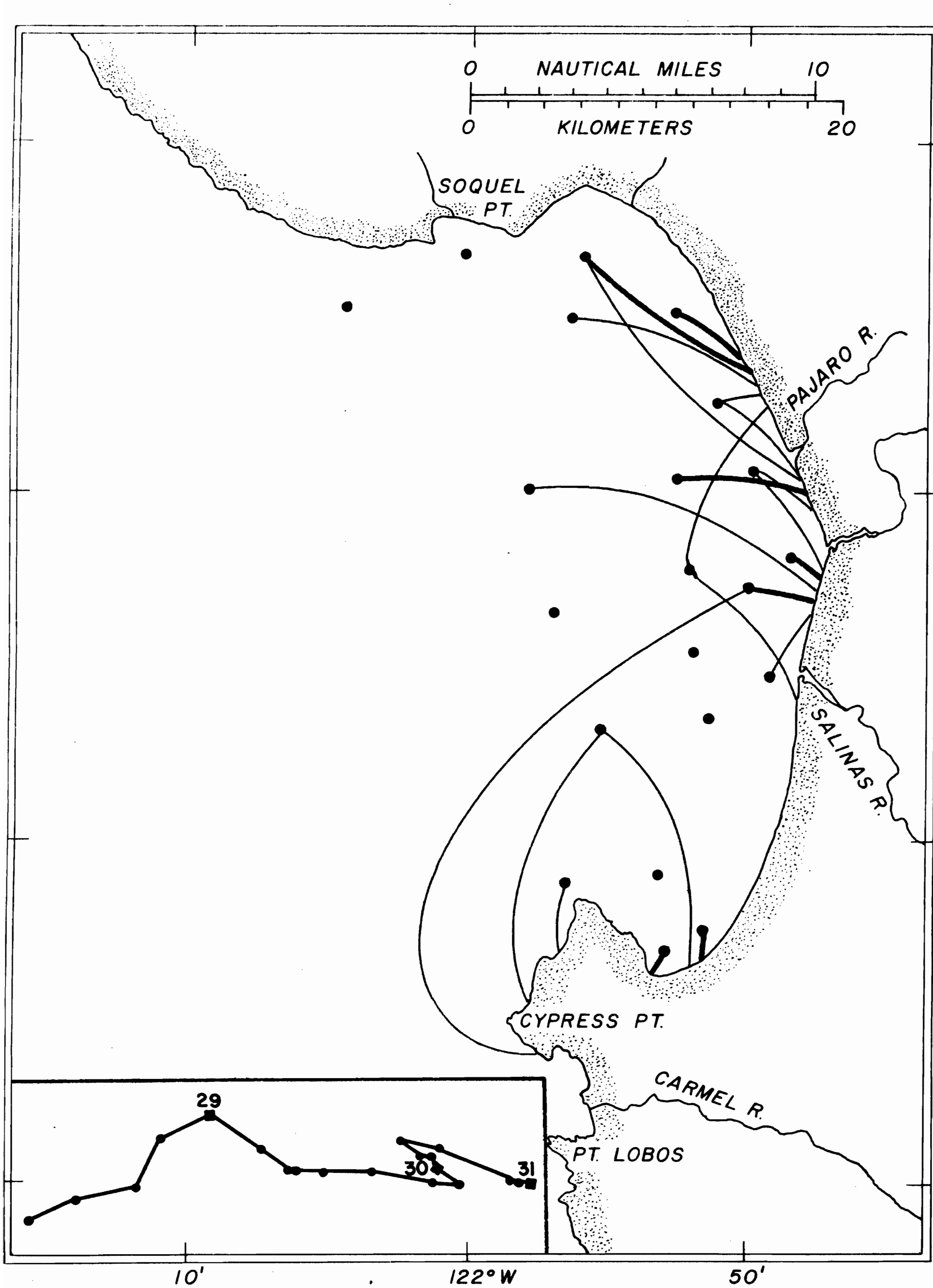
APPENDIX

MONTHLY DRIFT TRAJECTORIES IN MONTEREY BAY

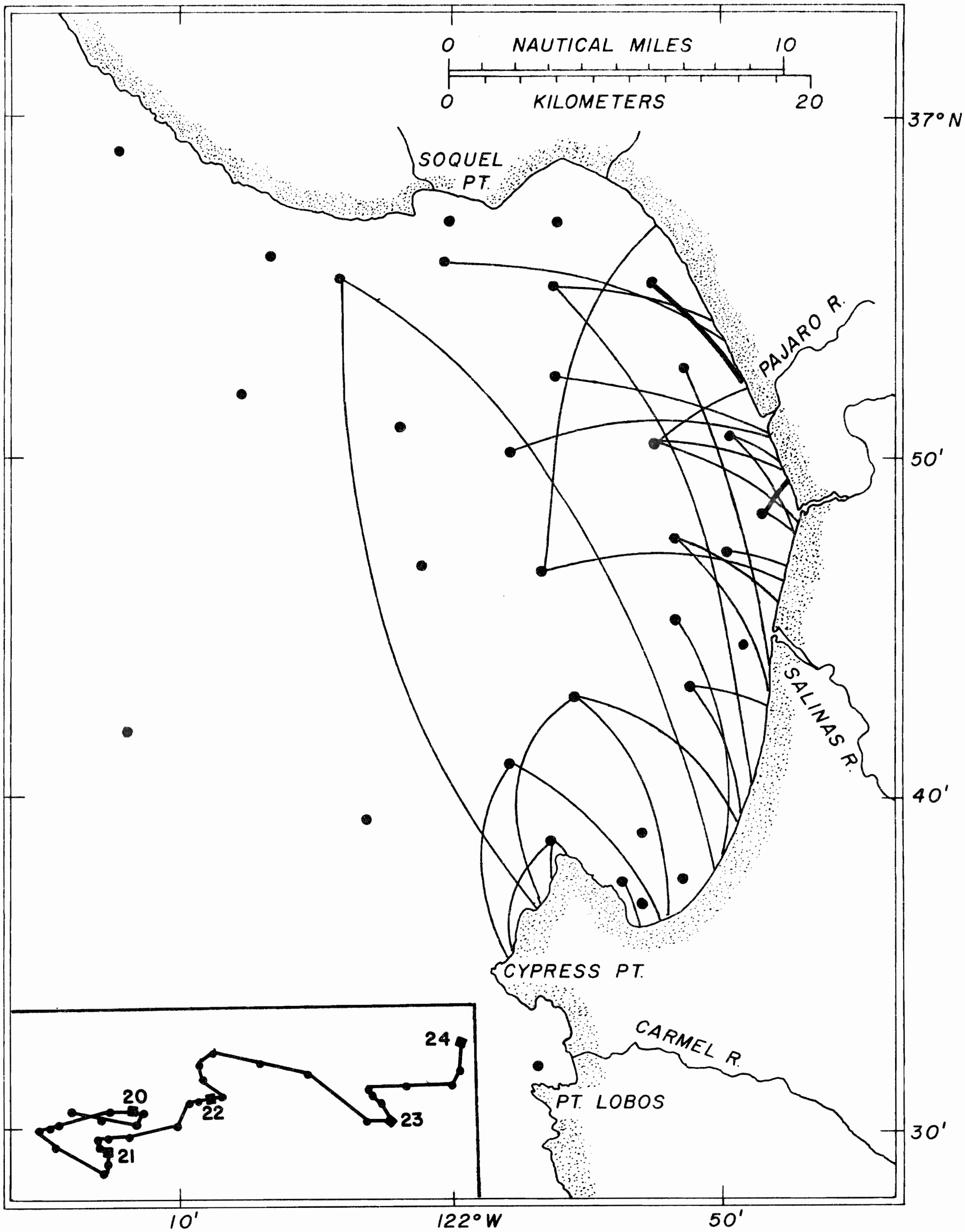
In this appendix, charts showing the inferred drift card paths are illustrated. Thick path lines indicate that more than 30% of the cards released at that station were recovered in the indicated coastal sector. Solid circles without path lines indicate no cards were recovered.

Inserts show the hypothesized progressive drift of cards at 3% of the wind velocity. Solid circles indicate the relative position at three hour intervals, and squares the day of the month after drift card release. However, during periods of low wind velocities, when two or more positions coincided, only one position is indicated. Wind data are from an elevation of 60 m at Moss Landing, California.

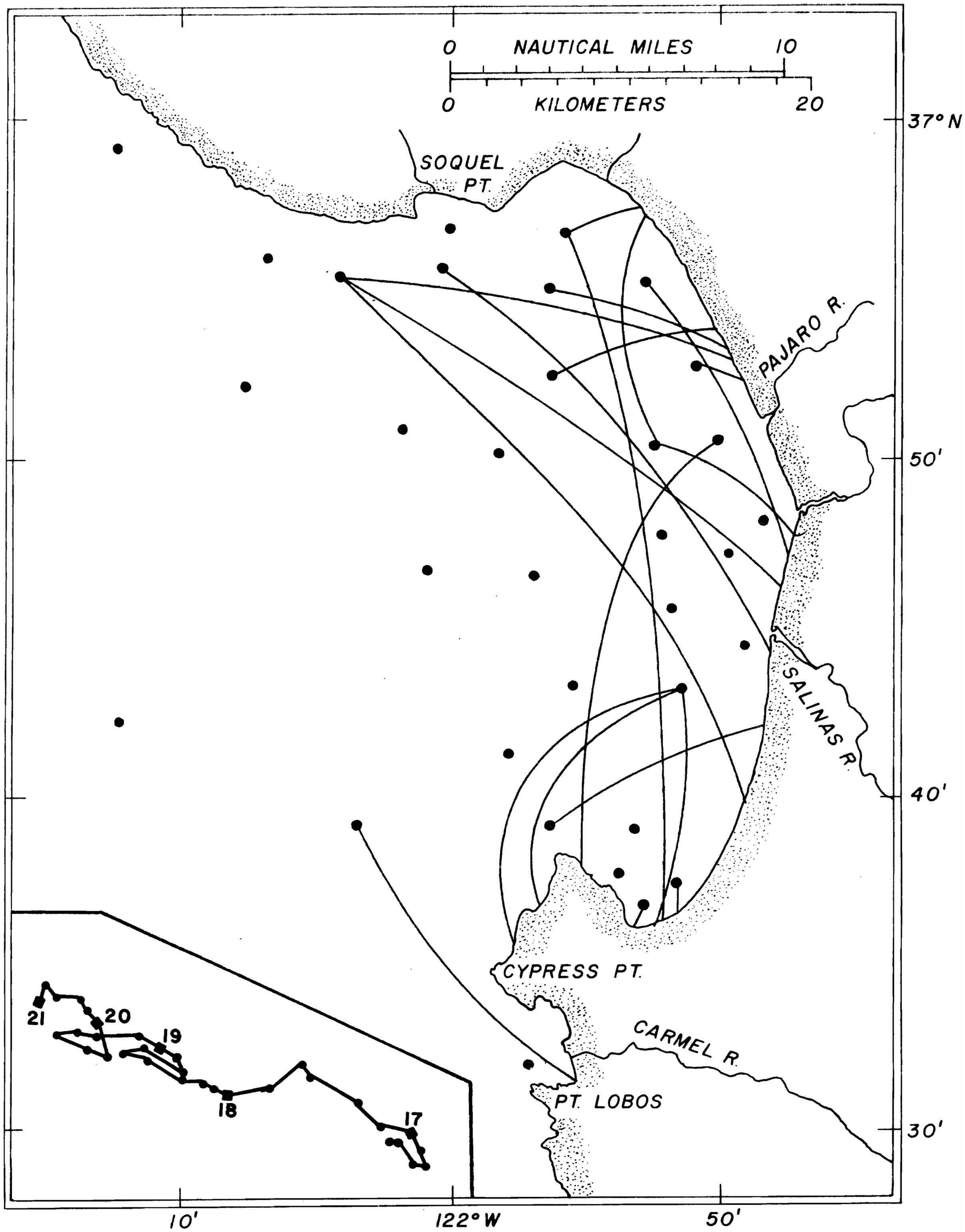
To simplify drafting, months of numerous returns or of complex drift card paths have been illustrated on two different charts.



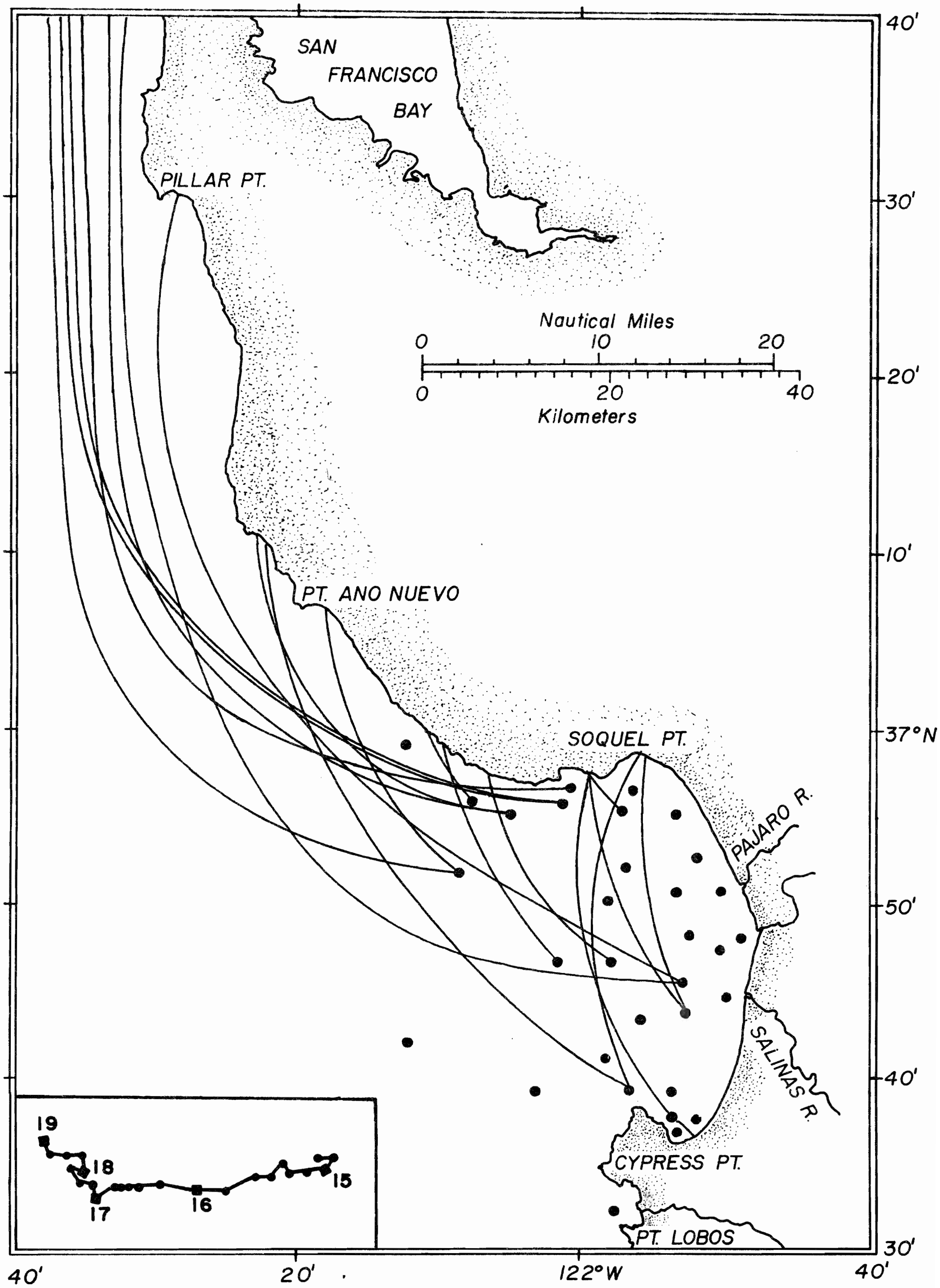
Inferred drift card paths during September 1971. Insert shows progressive drift of cards at 3% of the wind velocity.



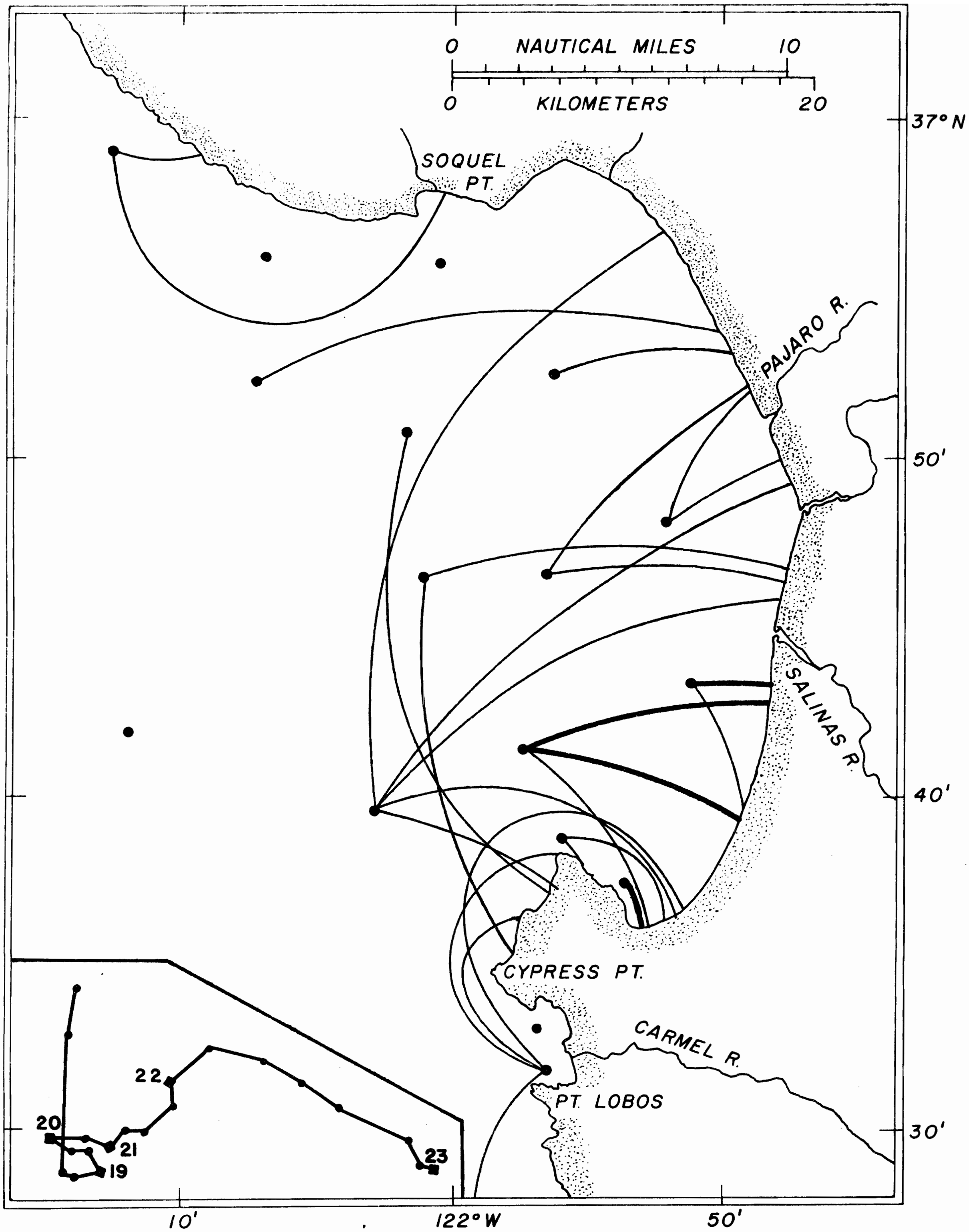
Inferred drift card paths during October 1971. Insert shows progressive drift of cards at 3% of the wind velocity.



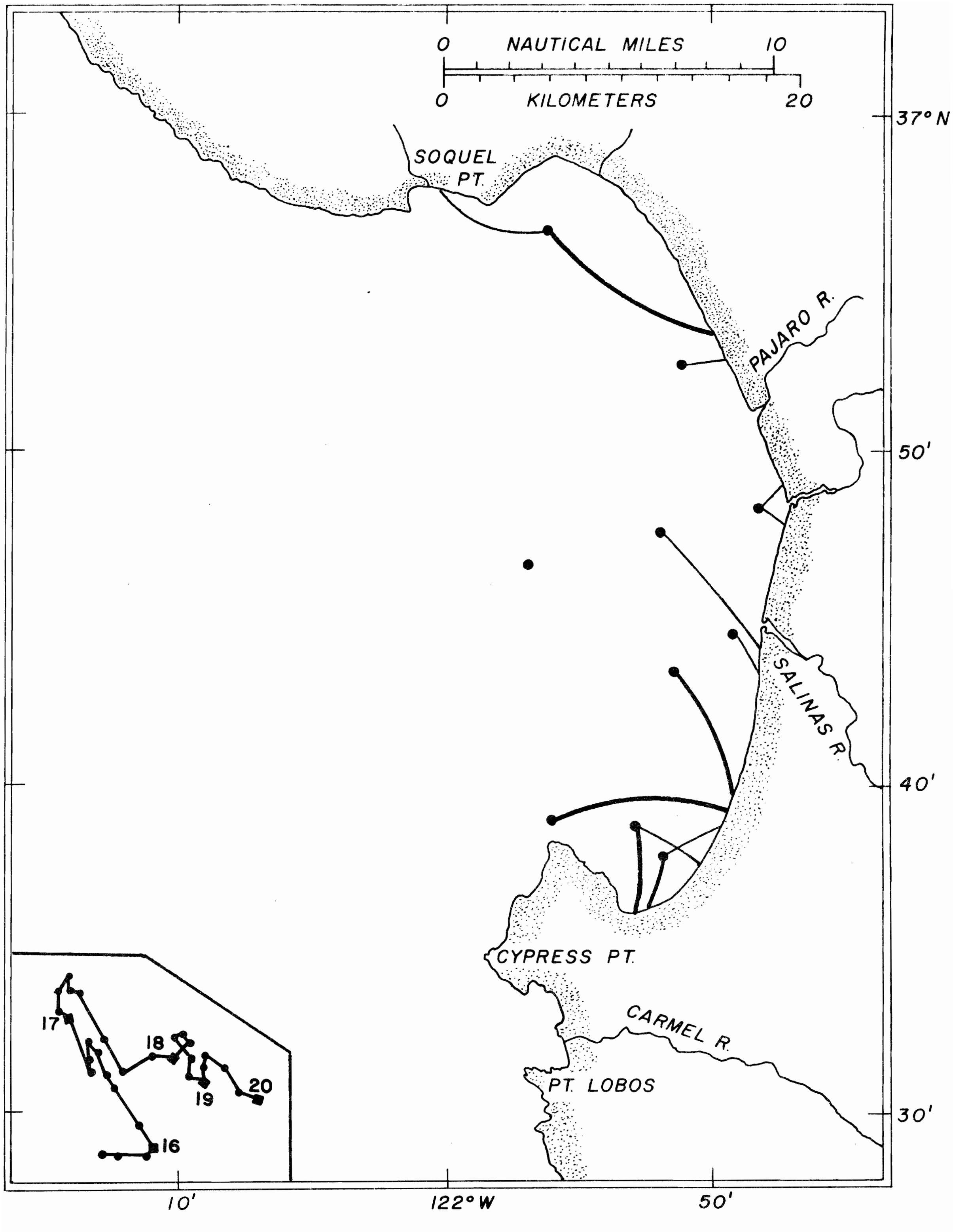
Inferred drift card paths during November 1971. Insert shows progressive drift of cards at 3% of the wind velocity.



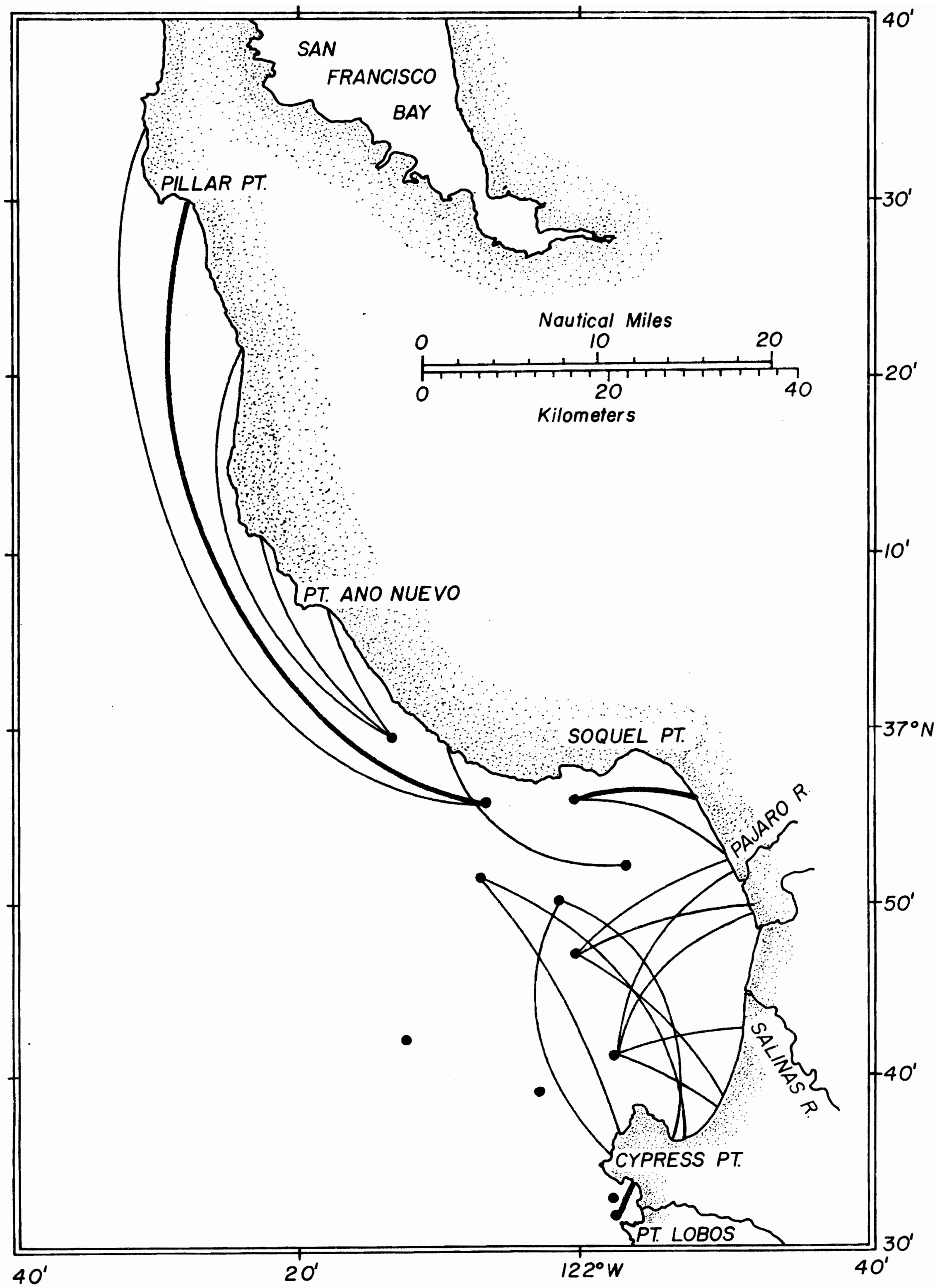
Inferred drift card paths during December 1971. Insert shows progressive drift of cards at 3% of the wind velocity.



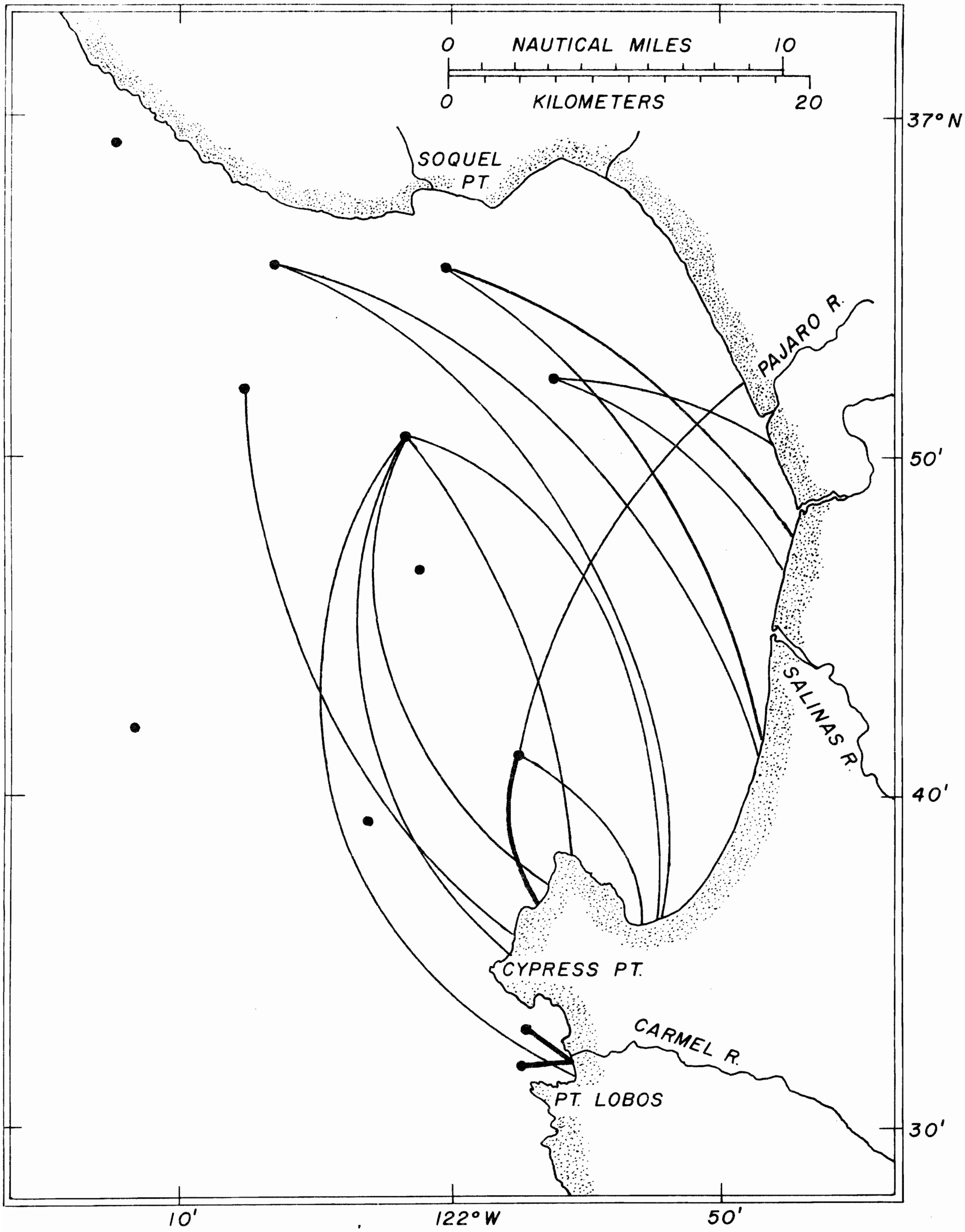
Inferred drift card paths during Janaury 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



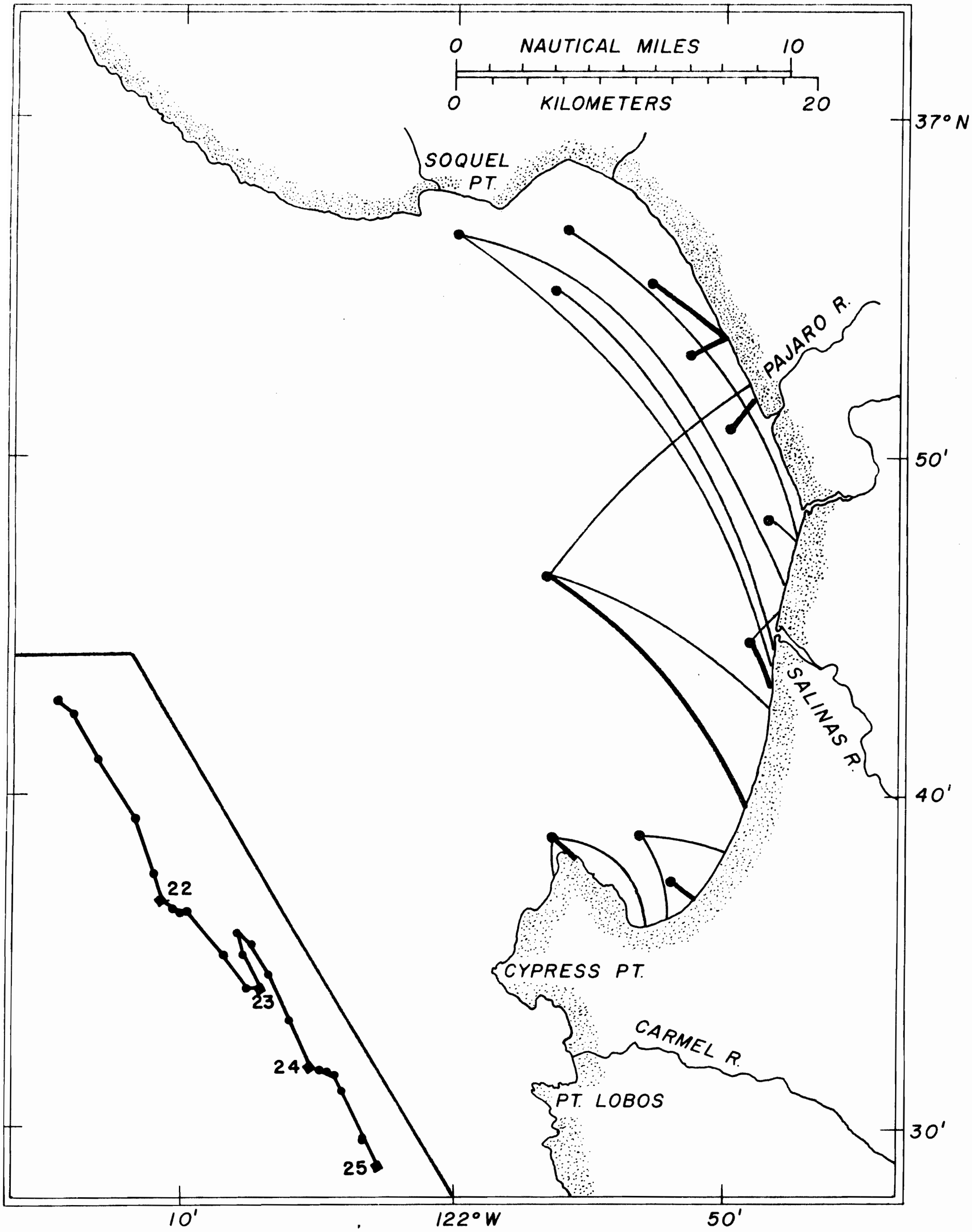
Inferred drift card paths during February 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



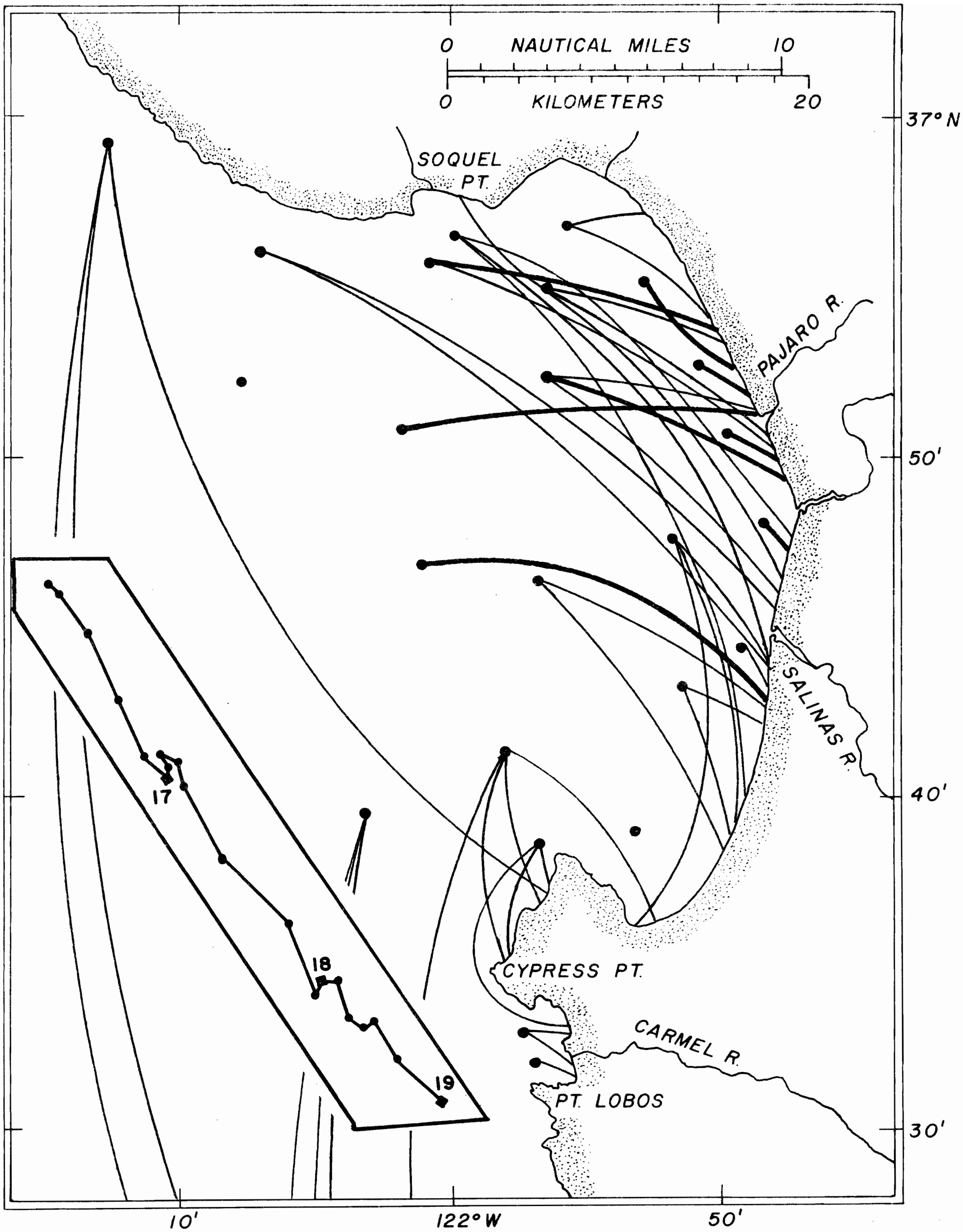
Inferred drift card paths during February 1972.



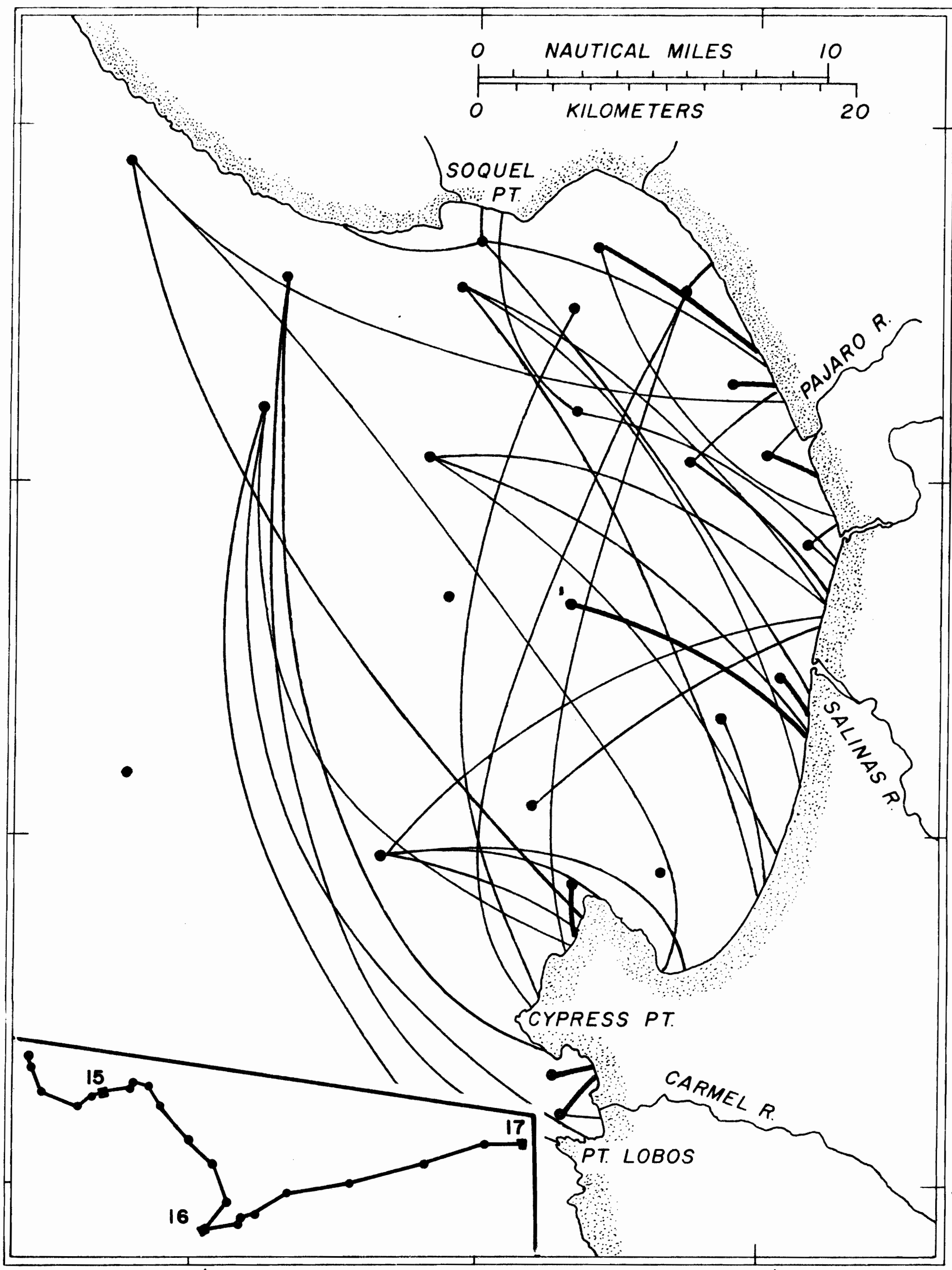
Inferred drift card paths during March 1972.



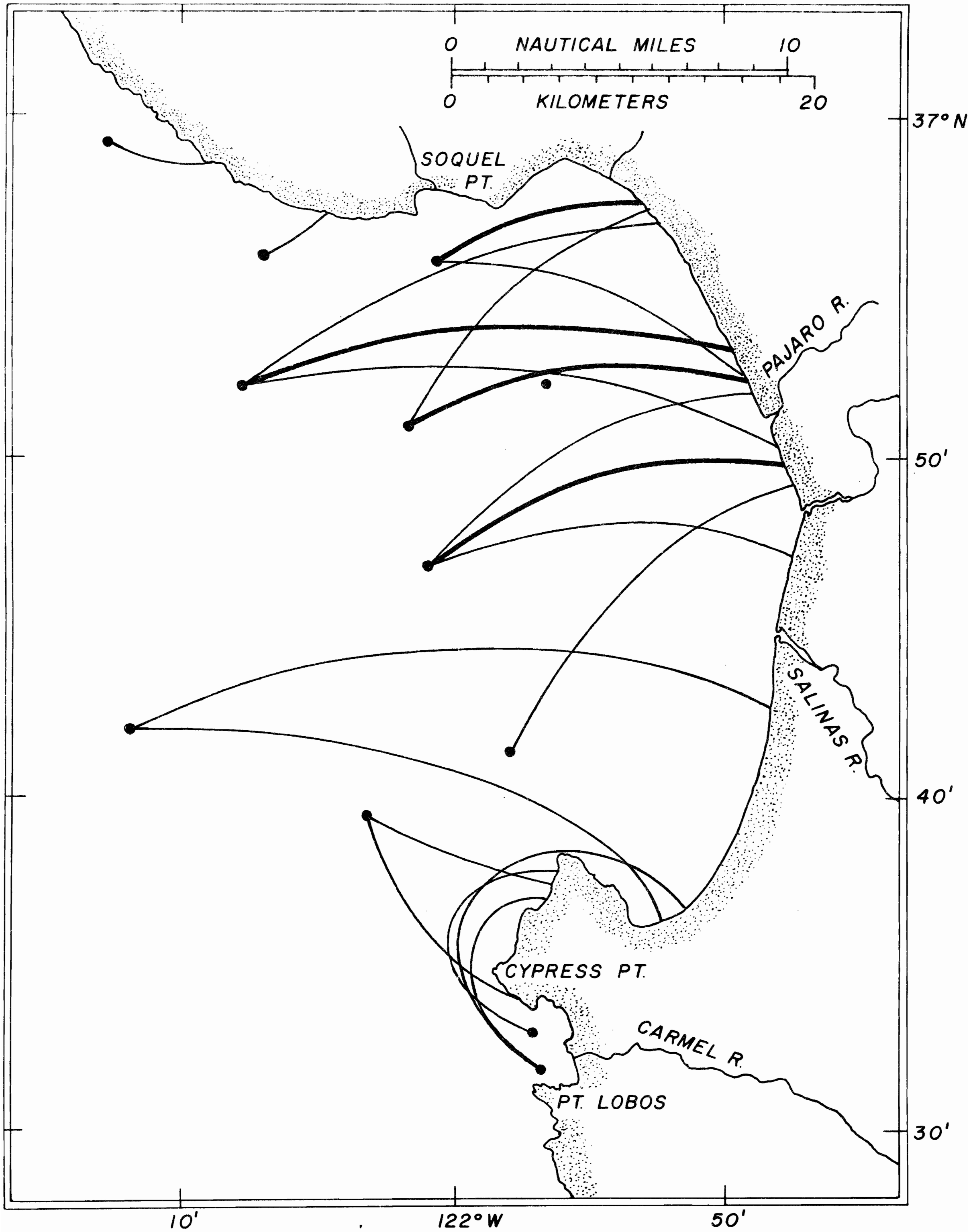
Inferred drift card paths during March 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



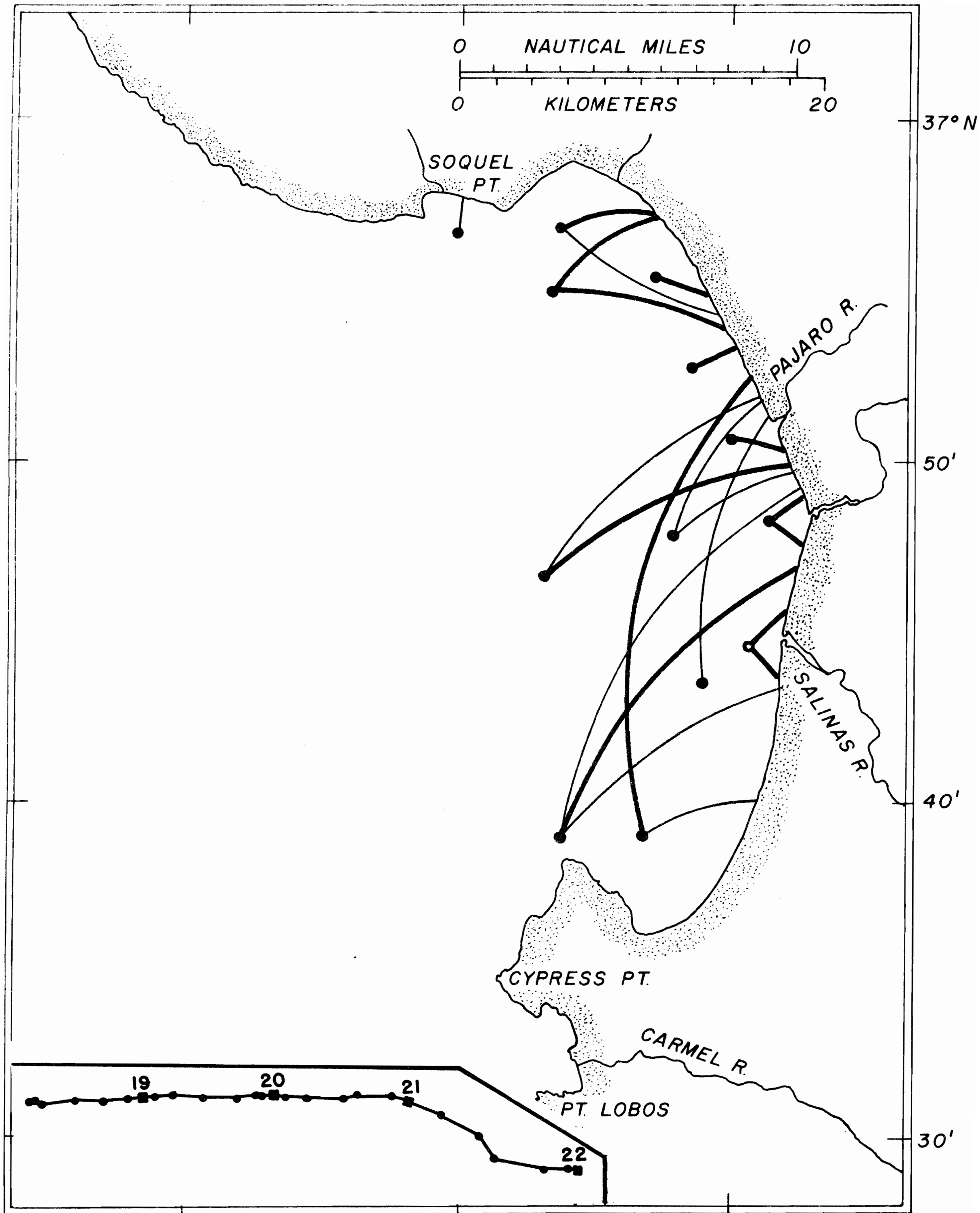
Inferred drift card paths during April 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



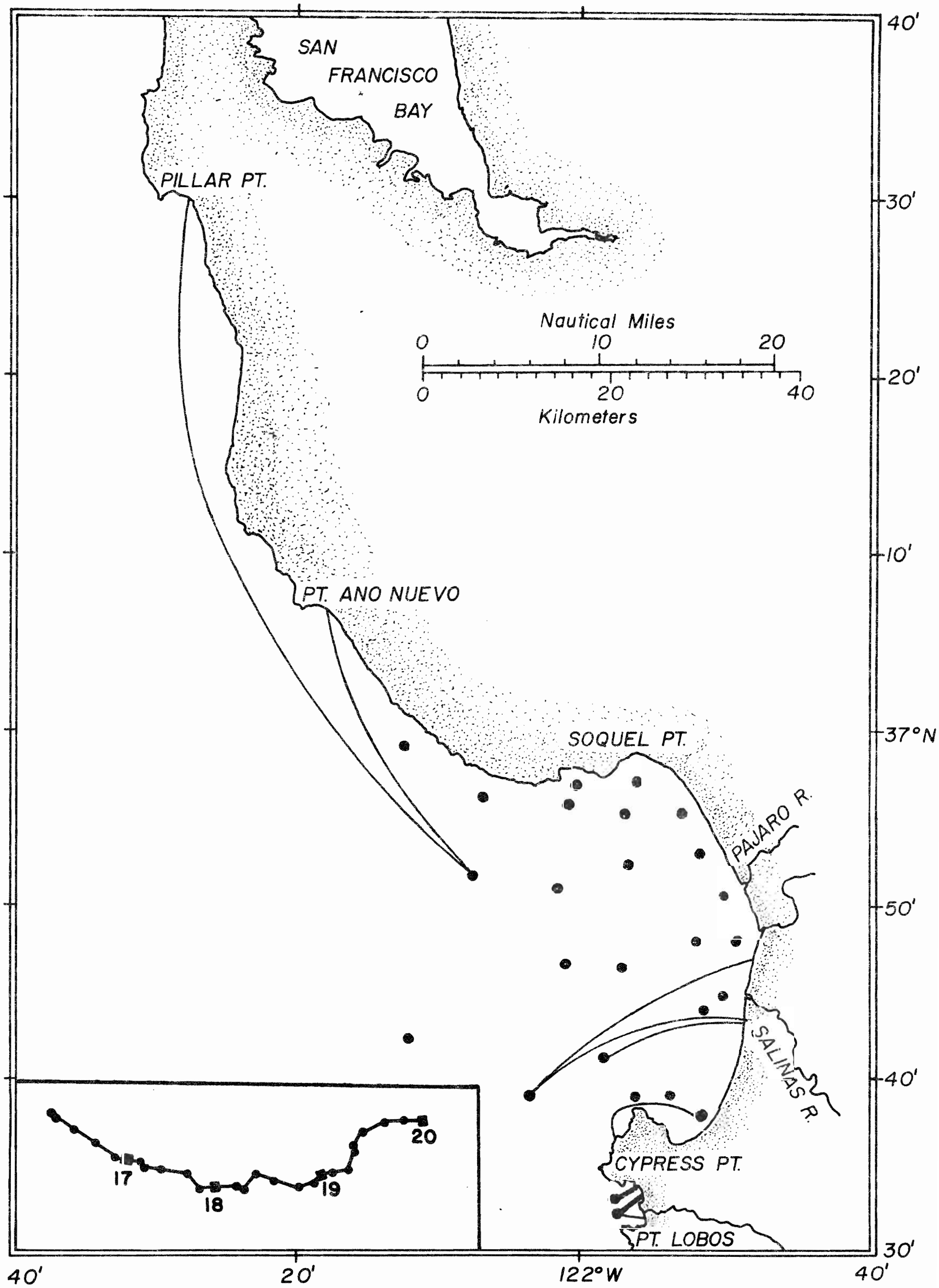
Inferred drift card paths during May 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



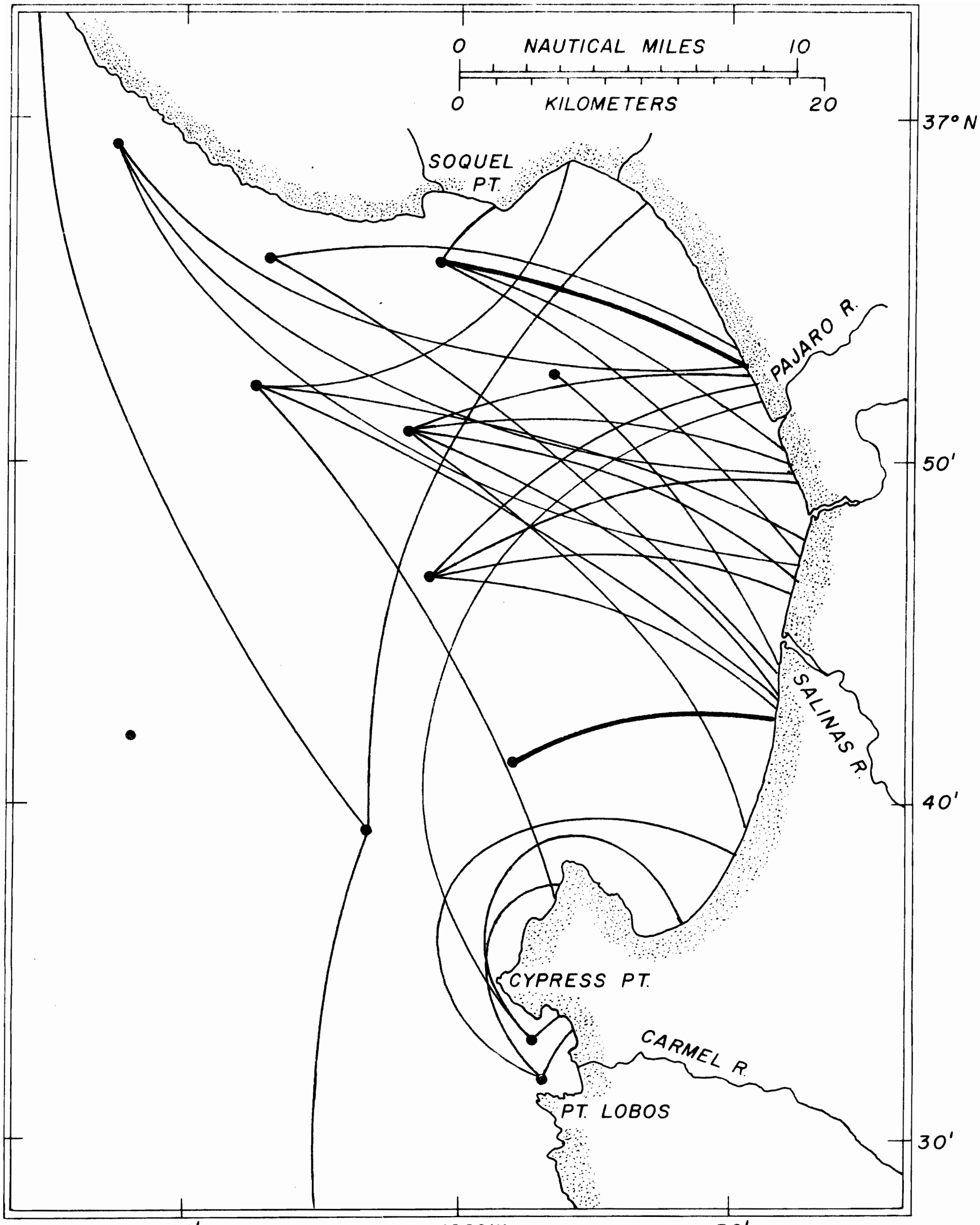
Inferred drift card paths during June 1972.



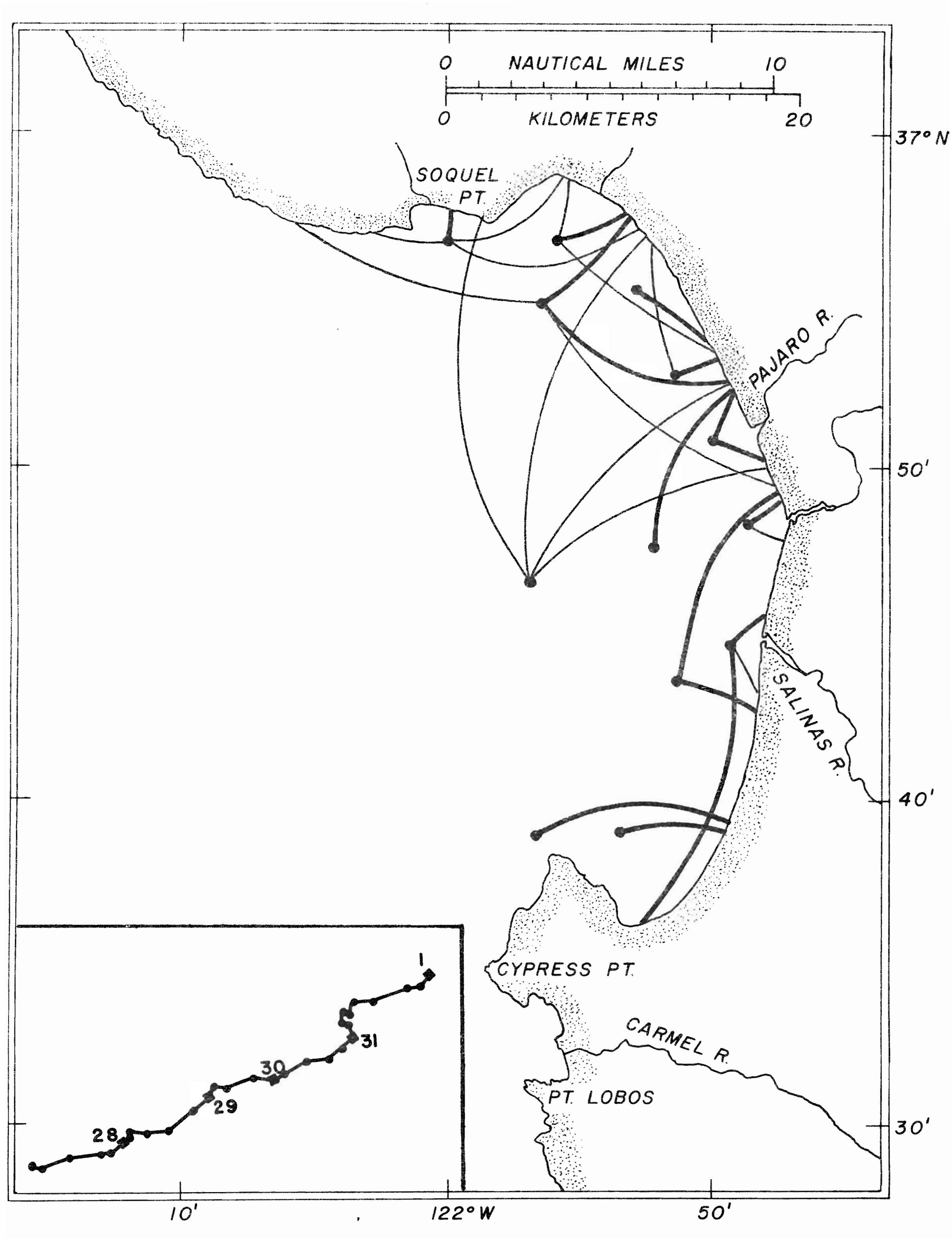
Inferred drift card paths during June 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



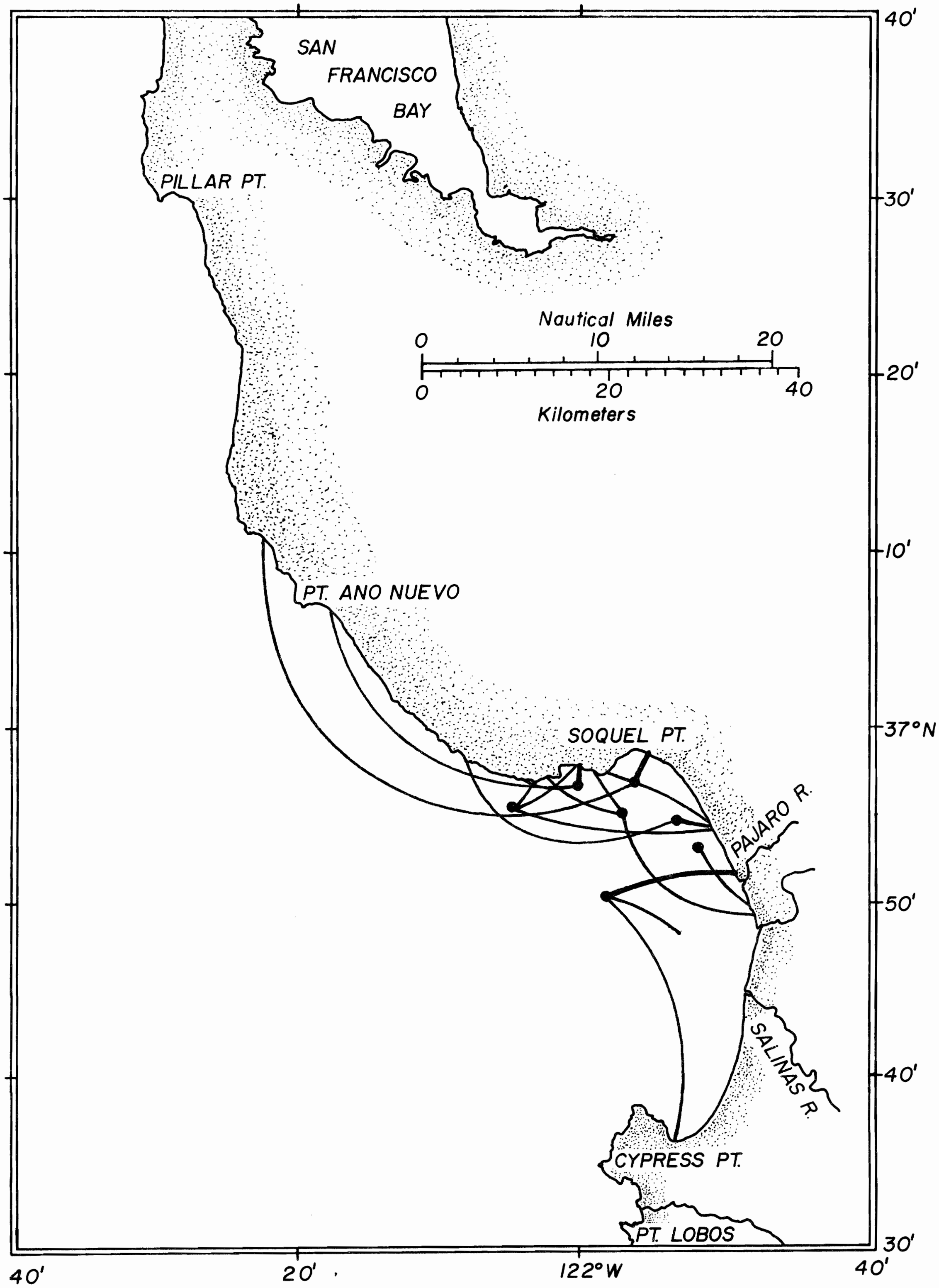
Inferred drift card paths during July 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



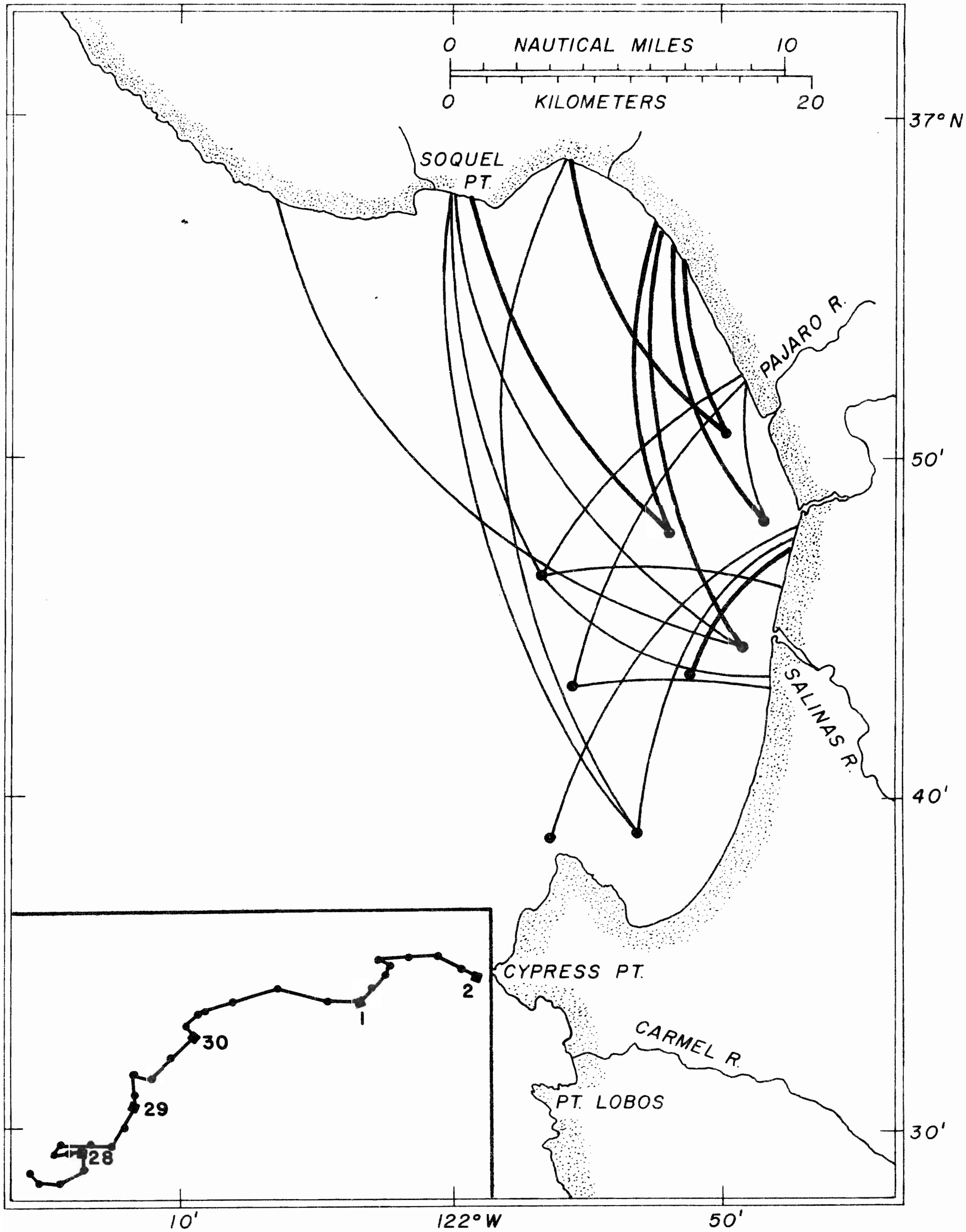
Inferred drift card paths during August 1972.



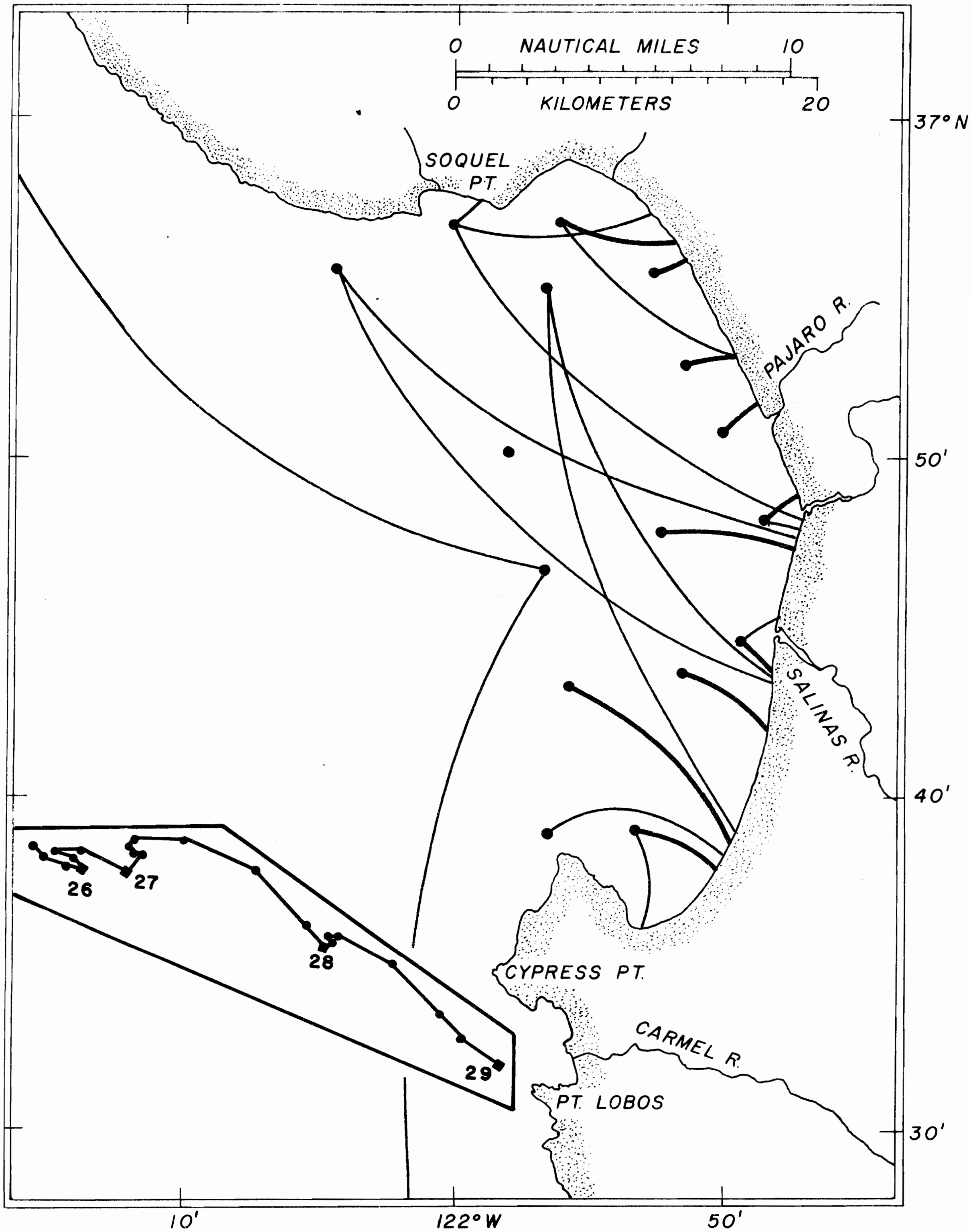
Inferred drift card paths during August 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



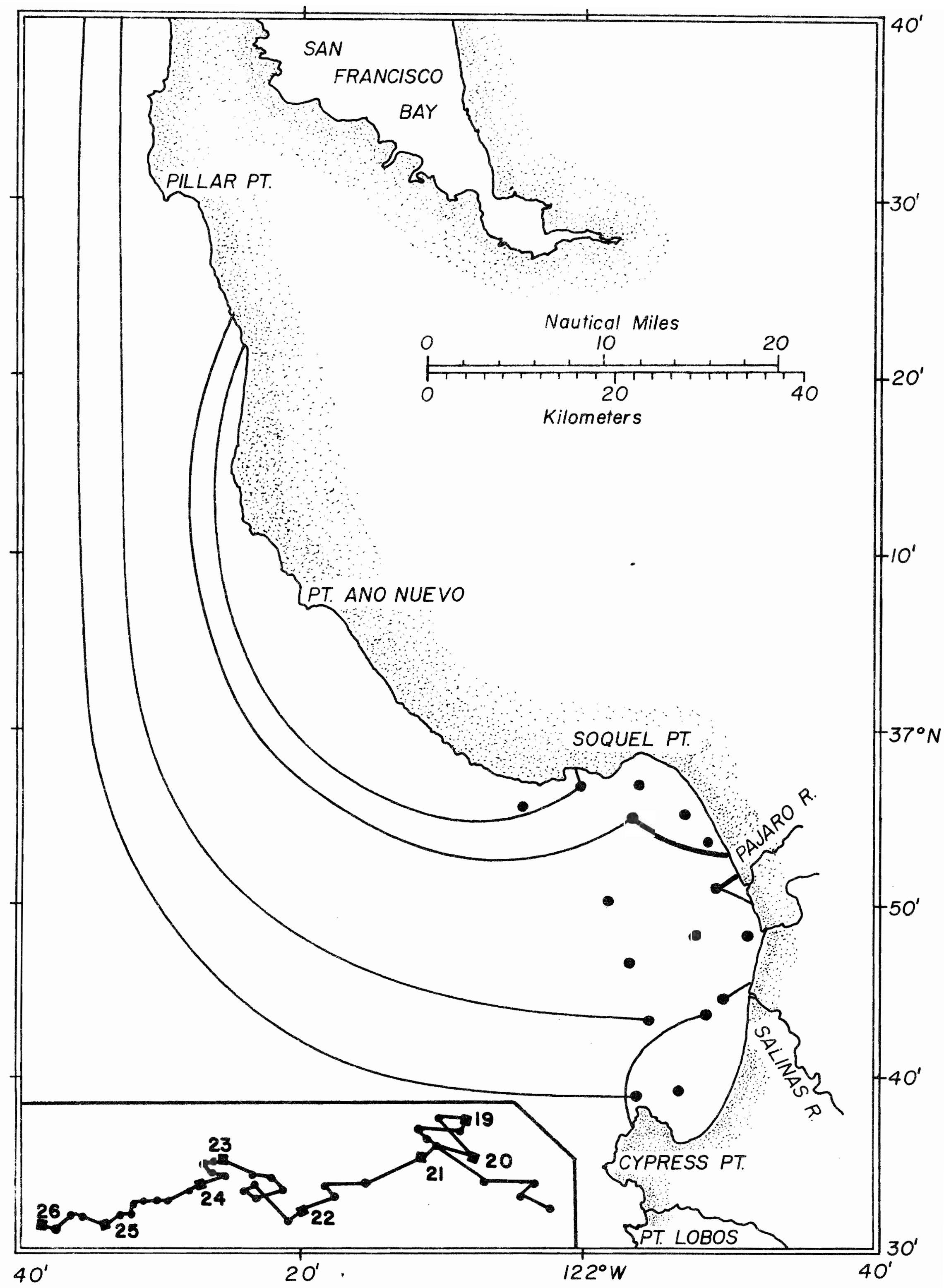
Inferred drift card paths during September 1972.



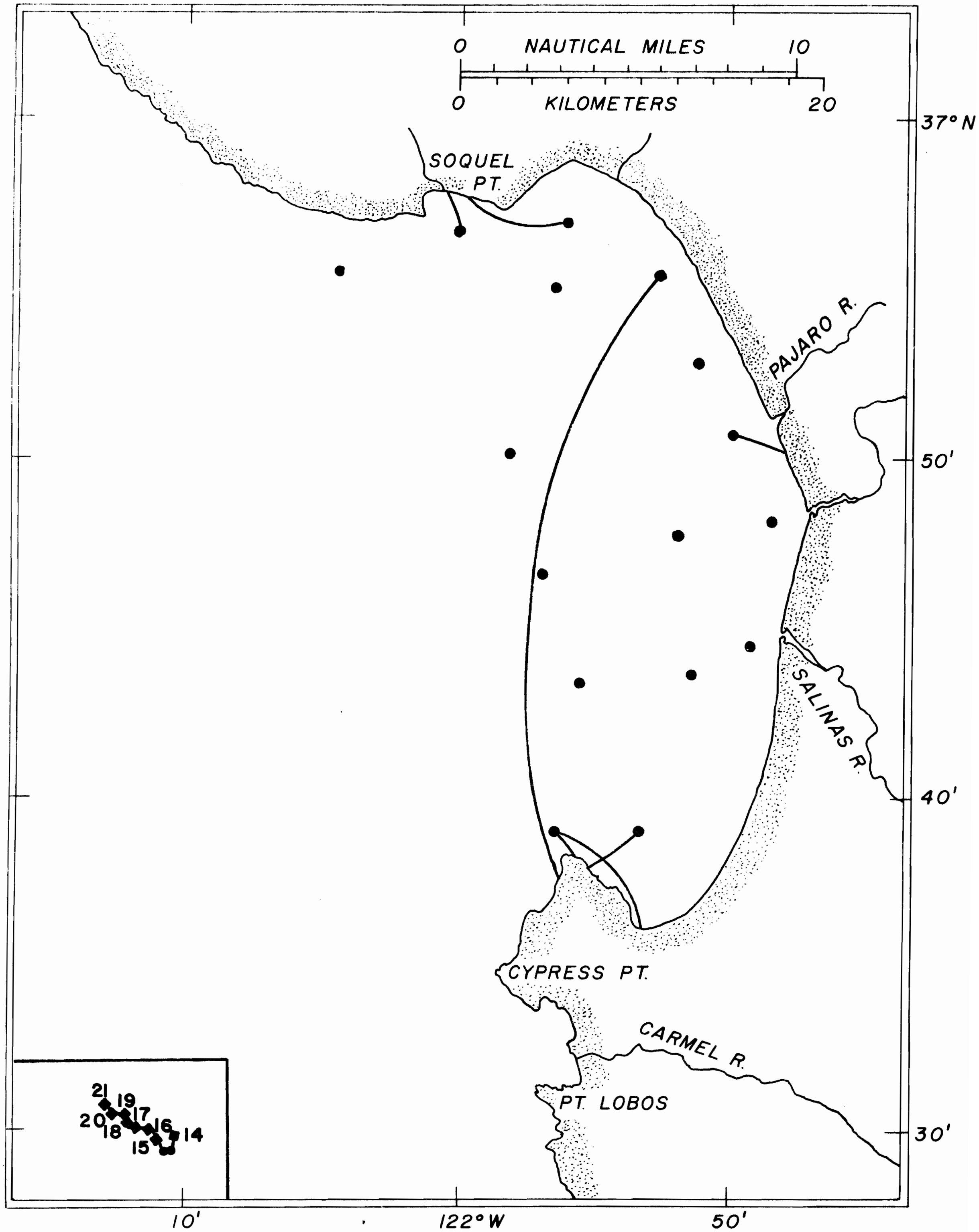
Inferred drift card paths during September 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



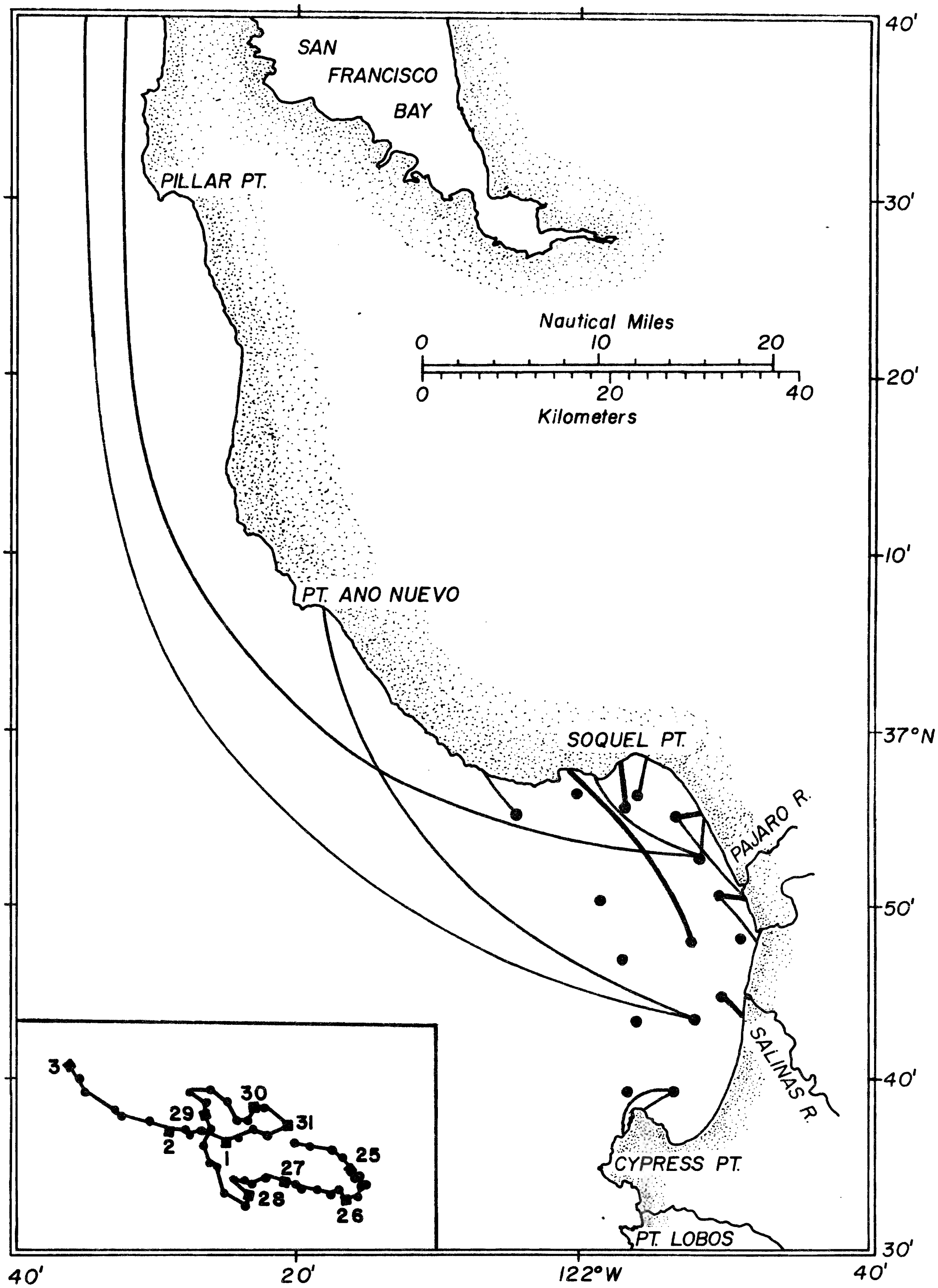
Inferred drift card paths during October 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



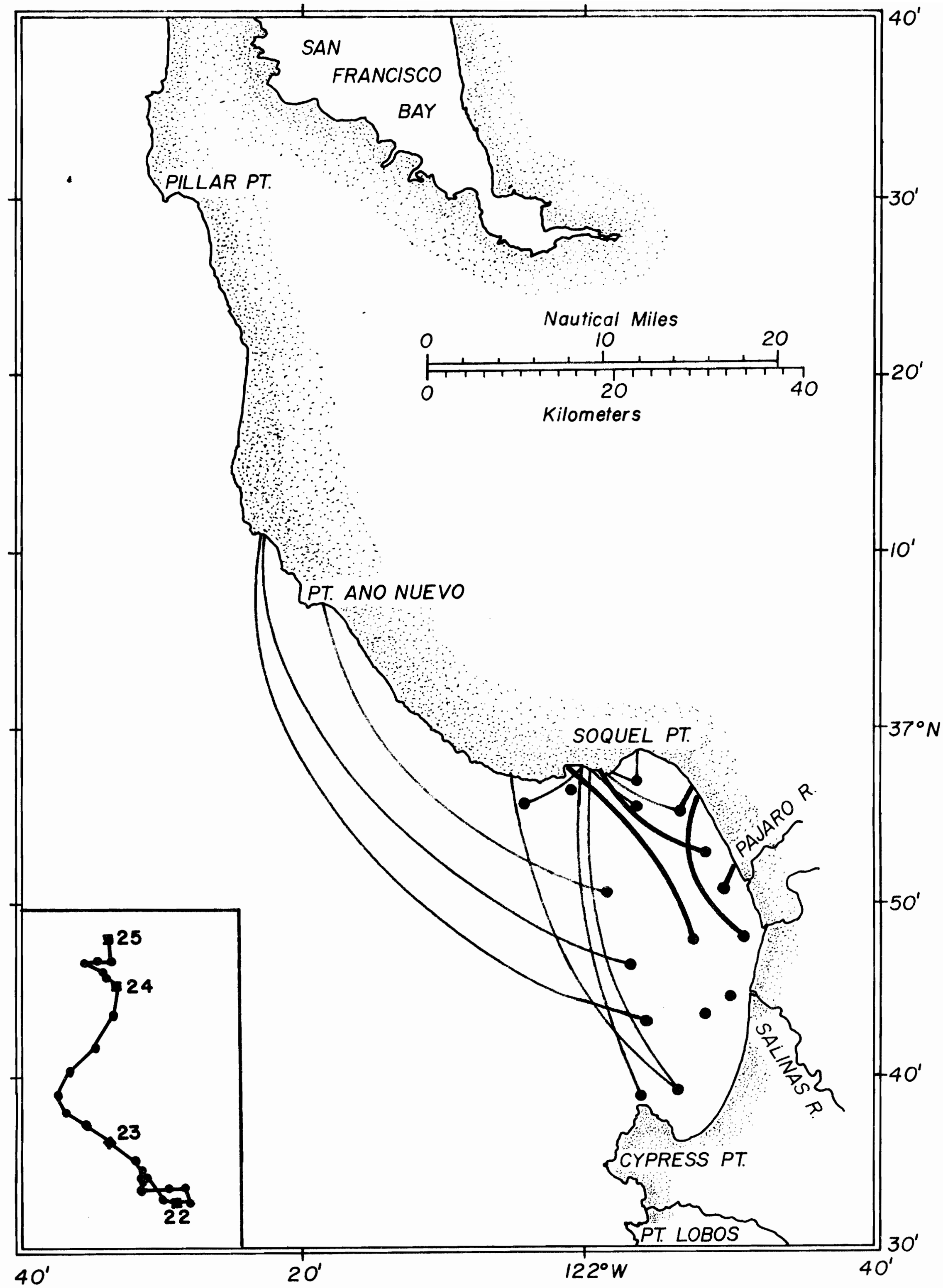
Inferred drift card paths during November 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



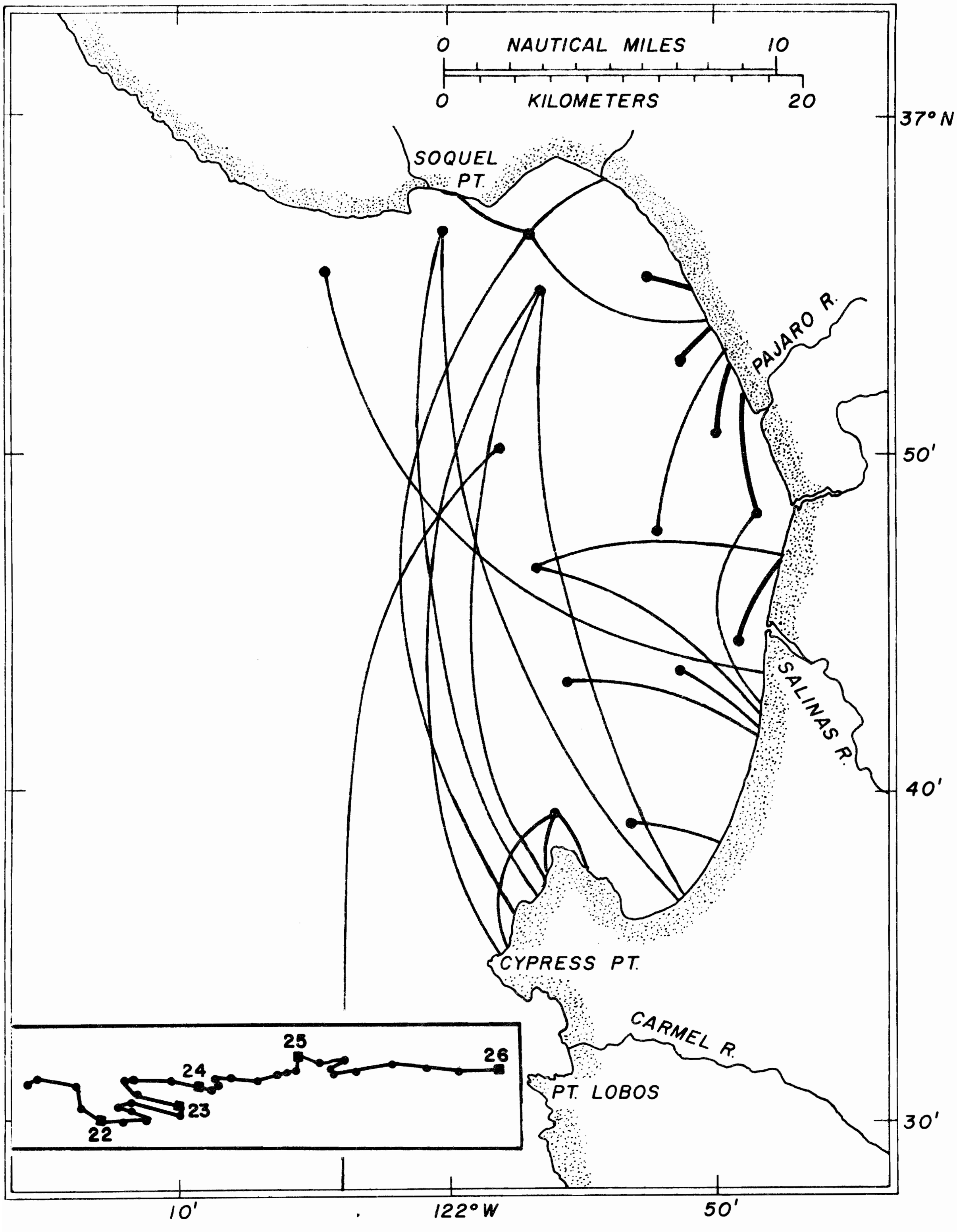
Inferred drift card paths during December 1972. Insert shows progressive drift of cards at 3% of the wind velocity.



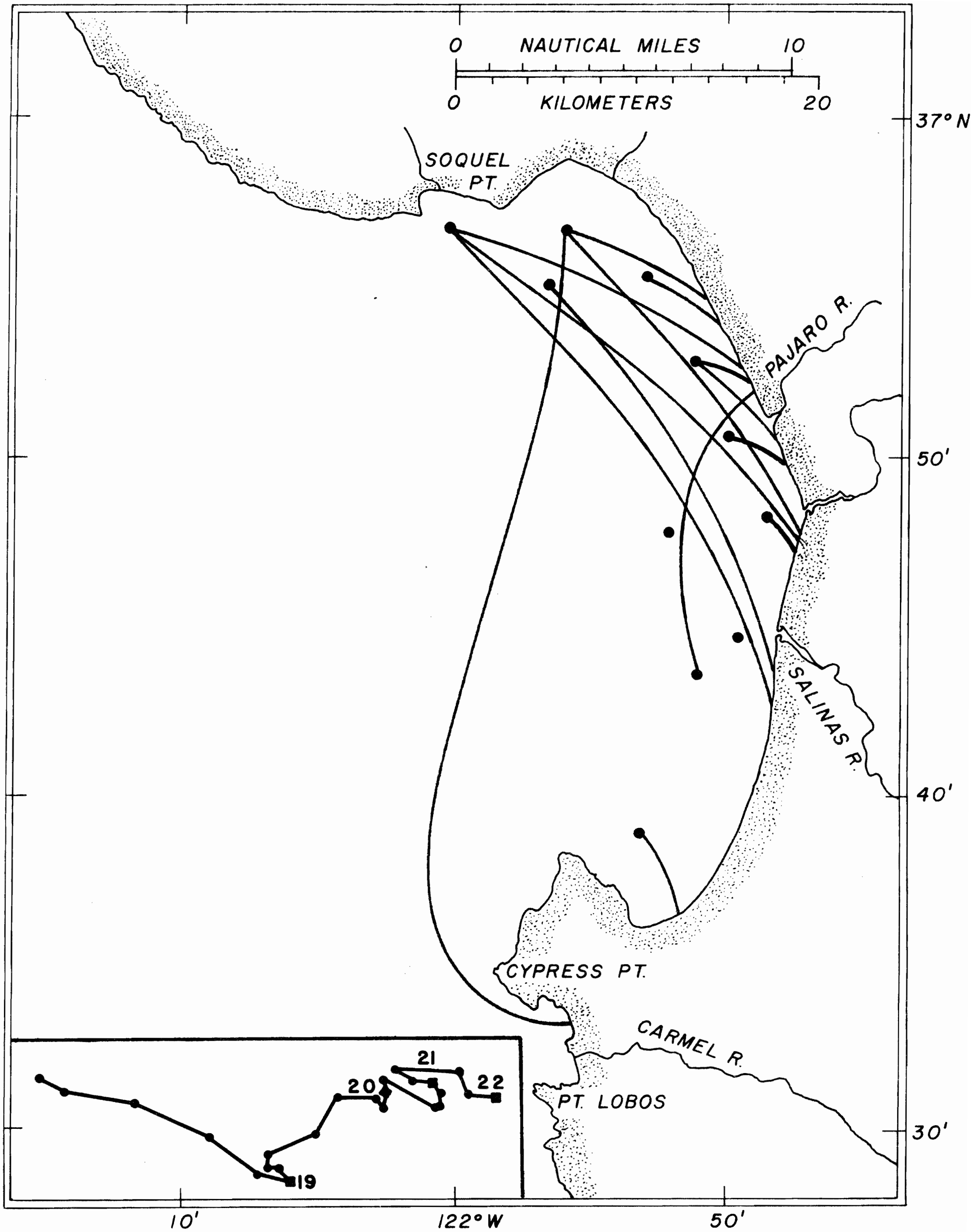
Inferred drift card paths during January 1973. Insert shows progressive drift of cards at 3% of the wind velocity.



Inferred drift card paths during February 1973. Insert shows progressive drift of cards at 3% of the wind velocity.



Inferred drift card paths during March 1973. Insert shows progressive drift of cards at 3% of the wind velocity.



Inferred drift card paths during April 1973. Insert shows progressive drift of cards at 3% of the wind velocity.